Insulation of
Electrical Apparatus

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BY

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FIRST EDITION
SECOND IMPRESSION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK AND LONDON
1941

INSULATION OF ELECTRICAL APPARATUS

PRINTED IN THE UNITED STATES OF AMERICA

THE MAPLE PRESS COMPANY, YORK, PA.

PREFACE

This volume can neither aspire to be a comprehensive treatment on dielectrics nor an encyclopedia of data on present-day insulation practices. In the field of dielectrics, much has been written on their behavior as a function of atomic structure; on the comparative characteristics of gases, liquids, and solids; on the causes of absorption, dielectric losses, and breakdown; or the inconsistencies of dielectrics that remain unexplained. Other books cover the properties of insulating materials under a variety of conditions, approaching the subject chiefly from an empirical angle, since it is difficult to extrapolate dielectric data or predict performance under untried conditions. The technical periodicals contain a wealth of information on special problems of application, the insulation of cables, of rotating machines, of transformers, or other apparatus—articles that are specialized and limited in scope. Still further technical writings discuss the long-time performance of insulating structures, observing the changes, mostly for the worse, that take place in insulation subjected to service conditions for extended periods of time.

The purpose of the present book is to give some of each of these viewpoints, a glimpse at several phases of the problems of dielectrics. The author has been associated for many years with several branches of the subject and has had to straddle, mentally, the fences between the divisions of research, materials, apparatus design, and testing. Knowledge of all these helps to give an understanding of the reasons for observed facts. This volume, then, might be termed a survey type of book, introducing an important subject and offering stimulation to the inquiring mind to pursue details of special interest still further.

In plan, the book opens with a résumé of the essential concepts of the nature and behavior of dielectrics. Next are presented a description and comparison of insulating materials, sufficiently specific to aid the designer in making a choice. Following this, the practices in application of insulation to the major types of electric power apparatus are described. In the usual sources

on design and construction of apparatus, the subject of insulation is very sketchily covered, if at all, and yet some of the most difficult problems in design often lie in the use of insulation. The final chapters cover testing methods and equipment. In the appendixes, tables and curves may be found showing properties of certain classes of insulation.

This book is written because of a need developed in the author's own experience. He was asked to prepare a course on insulation which would not be too theoretical and which would provide useful supplementary information to electrical engineering students interested in design and operation of power machinery. A search for a suitable textbook revealed nothing to fit the scope selected. Consequently the author undertook to prepare notes for instruction, which were later expanded to the present form.

The author is aware that he has not extended the boundary of scientific knowledge. From a large volume of material collected for the purpose, he has selected portions most useful to the student or engineer who seeks a working knowledge of insulation.

Grateful acknowledgment for invaluable help is given to the author's many engineering associates in the Westinghouse Electric and Manufacturing Company and to his colleagues at the Carnegie Institute of Technology; to the manufacturers who so graciously furnished data, illustrations, and suggestions; and to the authors and publishers who permitted inclusion of important parts of the text.

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February, 1941.

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INSULATION OF ELECTRICAL APPARATUS

INTRODUCTION

Functions of Insulation.—Of the four constructional elements in electrical apparatus, insulation is responsible for the most failures and probably presents the most perplexing problems to the designer. Electrical devices usually have two or more of the following functional parts:

1. Conductors.
2. Insulation.
3. Magnetic circuit.
4. Structural members.

Frequently a part performs more than one function. A conductor may be a structural part as well (stud of circuit breaker), or an insulator may be used as a mechanical support (bus-bar post). A conductor might rarely be provided with magnetic properties. In thermostatic relays where current through a magnetic conductor heats it to a temperature at which it becomes nonmagnetic, a protective operation may be initiated. Insulating materials, however, can hardly be conductors or magnetic members in any useful sense.

The chief function of an insulating member is to control the current flow in useful channels or, conversely, to prevent its "escape" in nonuseful or harmful paths. The effectiveness of control or restriction will depend on many properties of insulation, such as resistivity, dielectric strength, dielectric loss, and dielectric absorption. This multiplicity of points of vulnerability in insulation may account in part for the frequency with which insulation is the cause of electrical-apparatus failures.

Vulnerability of Insulation.—Our knowledge of the behavior of insulation is quite meager and much less exact than our understanding of the other elements enumerated. We can design

conductors with full confidence that they will be adequate electrically and mechanically and may even know how to calculate the inductance effects of magnetic fields set up by currents in the conductors. Similarly, we can quite well predict the performance of magnetic materials. We may have to make certain determinations of permeability, losses, and space factor by well-standardized methods. But except for a few disputed points, such as tooth pulsation losses in rotating machines, we are able to design magnetic circuits with certainty.

When we come to insulation, however, we know so little that we design with wide margins of safety, which might be termed "factors of ignorance." Insulation behavior, possibly, is affected by more variables than is that of other parts of apparatus, and the usual tests do not give us a true picture of operating conditions. Design, therefore, has to be based on experience, guided by tests which frequently yield conflicting data.

K. A. Reed, Chief Engineer, Electrical Division of the Hartford Steam Boiler Inspection & Insurance Company, in 1934 presented figures which represent a serious indictment of insulation. Analysis of 3,439 failures of electrical apparatus showed that insulation failure was responsible for 2,917 cases, or 84.9 per cent. Curiously, nearly half of all failures were in the stationary windings of rotating machines, which might seem like an easy job of insulation. (A further analysis of these results will be given later.)

This does not mean that we have neglected the study of insulation or that inferior materials or workmanship are commonly encountered. There is a wealth of literature on insulation (or dielectrics), and much research is now in progress. The National Research Council has an eminent Committee on Insulation which through Dr. J. B. Whitehead reports annually on the progress made in insulation. We conclude that the problems are complex, difficult, and not subject to simple or rapid solution. First of all, we are hazy about the fundamentals of dielectric behavior. The countless theories that have been developed, starting with Maxwell's classic two-layer dielectric, lift the clouds in limited areas and permit only a brief and fragmentary view of the whole scene. Without a thorough understanding, therefore, of what is taking place in insulation under electric stress, our solution to everyday problems must be approached through trial and error.

The designer therefore relies on masses of experimental data, covering imperfectly the scope of the variables that may exist. In time, of course, this accumulation of facts can be analyzed, as has been done in certain limited fields (such as insulating properties of gases), and treated inductively to establish the governing laws of behavior.

The chemical structure of much of our insulation adds to the difficulty. Great use is made of materials of organic origin. Natural products are complex in structure and variable in properties and have progressive changes in properties with time and temperature.

Though insulation is a silent partner in the operation of electrical machines, its soundness, reliability, and special functions (transfer of heat, for example) are so important to the active parts (conductors and magnetic parts) that it behooves us to obtain as complete an understanding as is possible of why insulators behave as they do and how we can most nearly approach the goal of making the insulation behave as we want it to.

Variety in Insulation Problems.—It is hard to imagine any electrical device without insulation. And the presence of insulation usually means a problem to solve. In the case of thermocouples, the voltage encountered may be only millivolts, but the problem of resistance of the insulation to chemicals or heat may require thought. The coating on steel laminations to prevent flow of eddy currents may not rate very high as an insulator when compared with quartz, but it must have physical toughness and adhesion to the steel and must not wear the punching dies. At the other end of the scale, the insulation of a million-volt X-ray tube both inside and outside the tube involves a serious study of stress distribution, electron bombardment, thermal transfer, creepage distances, and coordination of gaseous and vitreous insulation. A high-voltage transformer bushing must have insulation that has high dielectric strength and low power factor and yet must still be a rigid member to support the terminals at both ends. A balance must be obtained between strength against failure radially through the bushing and surface failure over the outside casing under varying weather conditions.

In the intermediate range, at distribution circuit voltages, the provision for adequate insulation in the desired space taxes the

designer's knowledge. Here, organic insulation is widely used and involves the need of preserving stability of properties. Protection against effects of heat, moisture, and oxidation is important. The questions most frequently asked of a proposed coil insulation, for example, are not what is its resistivity or dielectric strength, but how long it will retain its mechanical strength at operating temperatures, how it will stand abrasion and vibration, whether or not it can stand the punishment of automatic winding machines, whether or not the impregnating material will resist oil and chemicals. Weakness in any of these factors will ultimately lead to electrical failure. Thus, each type of apparatus has its own peculiar vulnerable points and its own means of protection. We hope to develop the idea further that, though high-voltage engineering involves spectacular and absorbing problems, even the common articles such as snap switches often bring up insulating requirements difficult enough for any ambitious engineer to tackle. Even the common attachment plug for electric irons is not yet perfect.

Approach to the Study of Insulation.—There are two ways of approaching the study of dielectrics, or insulation. From the purely theoretical side, physicists and chemists have developed many hypotheses and theories to account for dielectric behavior. Their efforts to find out the "why" and to fit known experimental data into a pattern or a set of laws have done much to systematize our studies. Many theories have, however, proved untenable and have been referred to by some as "mathematical stunts"; yet this method of attack has its value.

The wholly practical view is that of the tester who obtains data on behavior of various insulating materials under limited specific test conditions. This method, without a correlation and interpretation, is of limited usefulness. The experimental and the analytical methods must supplement each other. In this way, we can hope to forecast behavior or extrapolate data with some assurance.

Our treatment of the subject, we hope, will be a combination of the two and will offer practical, useful information in a way that will show as much of the "reasons why" as can be learned.

We shall spend a little time trying to understand the most important theories relating to dielectric behavior, not because any of them is perfect, but because they are associated with

prominent scientists such as Maxwell, Hopkinson, Pellat, von Schweidler, and Wagner. They also represent steps in the development of a fundamental understanding of dielectric phenomena, as a basis for later application. For example, a study of the theories on dielectric absorption may reveal a means of controlling this property in commercial insulation. J. B. Whitehead says, "The explanation of dielectric absorption stands out as the great unsolved problem in our efforts to control and design insulation for electric circuits and machinery."

Insulators and Conductors.—Electronically speaking, insulators are substances in which electrons are not easily dislodged from nuclei, as contrasted with conductors in which electrons easily move to the highest positive potential.

There is no sharp dividing line between insulators and conductors, but there is a wide range in specific conductivity from the best conductors to the best insulators. For example, though the range in conductivity among metals may be 60 to 1 (copper to mercury), the ratio between metals and good insulators is many times that. Copper has a conductivity 10^{24} times that of hard rubber. Electrical conductivity and thermal conductivity are apparently related, but the similarity is not wholly consistent. Electrical conductivity among insulating materials varies over a much wider range than thermal conductivity. For example, glass is a better conductor of electricity than porcelain, but a poorer heat conductor.

Understanding the Problem.—We have seen, therefore, that knowledge of electrical insulation is deplorably incomplete, and yet the successful performance of insulation is vital to electrical apparatus. Insulation problems appear in all types of devices, involving frequently an understanding of mechanical, thermal, and chemical behavior as well as electrical. Acquaintance with the present knowledge, both theoretical and practical, can do much to guide the engineer in the proper selection and use of insulating materials so that he may avoid failures in operation of his equipment.

CHAPTER I

DIELECTRIC PHENOMENA

Are the terms "insulation" and "dielectrics" synonymous? First of all, the word "insulation" must be of course qualified by the word "electrical" to avoid confusion with thermal or acoustical insulation. We find "insulation" used commonly in engineering literature, particularly in discussions of apparatus and conductors. "Dielectrics" occurs as the preferred designation in more purely scientific writings, particularly on the subject of electrostatics. The word itself implies action of electric force across a medium between separated electrodes. One might therefore conclude that "dielectrics" is a word associated with fundamental theory and endowed with more academic dignity, whereas "insulation" is a practical and vernacular word; but such a distinction is not warranted. We find "dielectrics" used frequently in simple descriptions of high-voltage apparatus and phenomena and in data on static capacitors. There is a tendency toward using "dielectrics" where high potentials or materials of superior properties are concerned, but no sharp definition can be made. The answer to our question, then, is that for our purposes the terms are interchangeable.

Before we commence the specific task of presenting a picture of the insulation of electrical apparatus, we shall recapitulate the essentials of the present understanding of the behavior of dielectrics (insulation); and, through such a procedure, recognition of the limitation of our knowledge will emerge. Demonstration of this lack will appear when the effects of time, temperature, and other variables are related (Chap. III).

A necessary prelude to the subject of dielectric behavior is the presentation of terms and their definitions. It is not our intention to give a comprehensive treatment of electrostatics, including the fundamental derivations available in many excellent college textbooks on physics. We shall limit our glossary of terms to usable and simple descriptive definitions which will be the tools for future discussions.

Every science or its subdivisions finds need for a specific vocabulary. One has only to listen to discussion of the professions (medical, for example) to realize the handicap of a layman in discussing the subjects involved. The object of technical words is not to confuse, as it might seem, but to clarify. Long, indefinite statements can be cut to single words which have definite, uniform meanings. It is obvious that "tonsillectomy" is a much more direct, useful, shorthand word than the layman's awkward "operation of having one's tonsils cut out." Likewise, electrical engineers find the term "potential" a definite concept, superior to loose statements about "something that makes current flow in a wire," which is neither accurate nor inclusive. Thus, we recognize the inherent value of scientific vocabularies. In the study of dielectrics we need certain words, and definitions for them, to describe the basic concepts. Some terms (for example, "potential," "intensity," "displacement") are old and well known. Others, such as "defect angle" and "loss factor," are of recent origin.

Following a method resembling that of an encyclopedia rather than a physics textbook, we shall present in the following paragraphs the most common concepts. Since there is often a "rugged individualism" among scientists that is manifested in the conflicting use of letter symbols, it becomes necessary to assume the designation most commonly used and try to remain consistent.

The **potential** (V) at a point is the work done against electrostatic forces in moving a unit positive charge from an infinitely remote point to a given point, and it is equal to the potential energy of unit charge at that point.

Electric intensity (E) is a measure of force due to a dielectric field resulting from electric charges. It is a vector quantity in the same direction as the lines of the field and is numerically equal to the force on a unit charge at the point.

The **potential gradient** (g), or the drop of potential per unit distance from a charge, is equal to the force at the point and opposite in sense to the electric intensity.
Then,

$$\frac{dV}{dr} = -E.$$

The gradient dV/dr is usually designated by g.

Capacitance (C).—A relation exists between charge (Q) and potential (V) in any electrostatic system that is commonly known as *capacitance.* The term is usually applied to condensers or capacitors (an assembly of electrodes and an intervening dielectric).

$$C = \frac{Q}{V}.$$

Dielectric Constant (K).—The kind of dielectric in a condenser determines the value of capacitance obtained. The *dielectric constant* can be defined as the ratio of capacitance of a condenser containing a given dielectric to the capacitance of the same condenser with a vacuum for dielectric (air is practically the same as a vacuum). A vacuum, therefore, has a dielectric constant of unity, and most other dielectrics some value above unity. The range is not so great as the resistivities of dielectrics, most common solid insulation coming within the range 1 to 10. Several liquids (*e.g.*, alcohols) and a few solids (notably titanium dioxide) have dielectric constants up to 100. In much engineering literature a symbol s.i.c. will be found, meaning *specific inductive capacity*, a term which was originated by Faraday and which is synonymous with dielectric constant (K). If we arbitrarily divide dielectrics into quality groups, the resistivities and dielectric constants would cover ranges as follows:

Group I.	Conductors.............	0 to 10^6 ohm-cm.	K = 30 to 100
Group II.	Semiconductors.........	10^6 to 10^{12} ohm-cm.	K = 6 to 30
Group III.	Good insulators.........	10^{12} to 10^{20} ohm-cm.	K = 1 to 6

Geometric capacitance is the constant value of capacitance of a condenser based on its dimensions and a definite dielectric constant of the dielectric medium. An example is the capacitance of two parallel plates which can be calculated to have a capacitance, in microfarads, $C = 0.088 \times 10^{-6}(KA/S)$, where A is the area in square centimeters and S is the separation in centimeters. This value holds for initial brief times of charge and discharge of the condenser. A condenser may have geometric capacitance if the dielectric is homogeneous and pure, but usual condensers have a value much higher than the geometric capacitance, sometimes five times as much. On alternating current, the apparent capacity approaches the geometric at increased frequencies. The

difference in capacity measurements at high frequency (*e.g.*, 10,000 cycles) and low frequency or direct current is a measure of absorption.

Anomalous dispersion is the decrease in dielectric constant with increasing frequency. It is frequently associated with polar substances (materials that are normally polarized even in the absence of a field). The dielectric constant of such materials may not decrease continuously with increase in frequency. There may be regions of anomalous dispersion occurring at several places in the range from power frequencies to optical frequencies. At other places the dielectric constant may be stable. In the optical range of frequency, dispersion becomes the decrease of index of refraction, which is related definitely to dielectric constant. $K = n^2$, where K is the dielectric constant and n is the index of refraction.

Displacement (D).—Another approach to dielectric constant is by way of the term "displacement." First let us form a physical picture of what happens. In an electric field, charges of the atoms are moved from their normal position by action of the field. This change in position of charges by applying the electric field, or the distortion of electric orbits, is called "displacement." The motion of charges constitutes a "displacement current," also called "charging current" and "polarization current." Now let us examine the mathematical picture. Displacement is related to the electric intensity by the factor *dielectric constant*, a term met before in describing the capacitance of a condenser.

$$D = KE.$$

From another viewpoint, displacement is the vector sum of electric intensity and $4\pi \times$ polarization (P) caused by the electric intensity E.

$$D = E + 4\pi P.$$

The total displacement, or electric flux density, is then the vector sum of two components, one due to the externally applied electric field E and one arising from the internal molecular polarization.

The analogous magnetic relations will be recognized. Flux density (magnetic) equals the sum of the magnetizing force H and $4\pi I$, where I is the internal induced magnetization, which in

turn equals kH, where k is magnetic susceptibility. Compare $I = kH$ with the electric field counterpart mentioned below, $P = kE$. From $\beta = H + 4\pi I$, we obtain

$$\mu \text{ (permeability)} = 1 + 4\pi k.$$

The electric relation is

$$K \text{ (dielectric constant or permittivity)} = 1 + 4\pi k.$$

In both cases, k is susceptibility.

Polarization (P).—In magnetic fields, we conceive north and south poles of a magnetic material being formed on elemental particles of matter and so oriented that north and south poles are separated and form magnetic couples having magnetic moments. A somewhat analogous situation in the electric field is commonly accepted. Under influence of an applied electric field, the centroid of the positive charges is at a distance from the centroid of the negative charges. The dielectric is then said to be "polarized." Polarization is mathematically described as the electric moment per unit volume, and the proportionality factor to electric intensity is called "susceptibility" (k). Certain materials having dielectric constants that vary with frequency are known to exhibit polarization even in the absence of a field and are called "polar" substances or substances having polar molecules. In nonpolar materials, polarization depends on the electric field and ceases when the field is removed. With polar dielectrics, a polar arrangement of charges exists normally without an exciting intensity, and further displacement occurs when E is applied.

Susceptibility (k) is the number or factor that relates polarization to the electric intensity causing it. The term is almost self-descriptive.

$$P = kE.$$

The units of electric intensity E, displacement D, and polarization P are all the same (dynes per unit charge), and vectorially they are all in the same direction in isotropic dielectrics. In terms of K, $k = (K - 1)/4\pi$.

Mathematical Relations.—It will be useful to summarize the mathematical relations connecting the above-discussed terms. In the c.g.s. system, physicists assume 4π lines of force emanating

from a unit charge. Other rationalized systems chose 1 line per unit charge. Obviously, the units of displacement derived cannot be the same. There seems to be a preference for 4π lines, which will therefore be adopted for the following relations.

1. Displacement is the vector sum of the electric intensity and $4\pi \times$ polarization.

$$D = E + 4\pi P.$$

2. Since polarization is proportional to the electric field ($P = kE$), then

$$D = E + 4\pi kE = E(1 + 4\pi k)$$

where k = susceptibility.

3. Since displacement is also proportional to electric field ($D = KE$, analogous to $\beta = \mu H$), combine with (1) and (2), and we have

$$D = KE = E(1 + 4\pi k).$$

Then,

$$K = 1 + 4\pi k.$$

Dielectric constant equals $1 + 4\pi$ times susceptibility; or

$$\text{Susceptibility } (k) = \frac{(K - 1)}{4\pi}$$

which is the more common form.

Gauss's Law.—Gauss's law states that the surface integral of the normal induction outward taken over any closed surface surrounding a charge $q = 4\pi q$. The proof will be found in any physics text. Many useful formulae involving simple geometric-form condensers such as parallel plates and cables can be derived from this law, such as the following:

1. Capacitance of parallel-plate condenser

$$C = 0.088 \times 10^{-6} \frac{KA}{S} \mu f$$

where A = area, sq. cm.
K = dielectric constant.
S = spacing, cm.

2. Capacitance of two parallel wires

$$C = \frac{0.0194}{\log_{10} (S - r)/4} \ \mu\text{f per mile}$$

where S = spacing.
r = radius of conductor.

S and r in same units (S is assumed large compared with r).

3. Single round wire, parallel to ground

$$C = \frac{0.03883}{\log_{10} (2H/r)} \ \mu\text{f per mile}$$

where H = height of wire above ground.
r = radius of wire.

H and r in same units (H is assumed large compared with r).

4. Single conductor and sheath

$$C = \frac{0.0388K}{\log_{10} r_2/r_1} \ \mu\text{f per mile.}$$

r_2 and r_1 in same units.

5. Sphere to earth

$$C = \frac{1}{1/R - 1/(2H - R)} \times \frac{1}{9 \times 10^5} \ \mu\text{f}$$

where R = radius, cm.
H = height above earth, cm., to center of sphere.

Where H is very large compared with R,

$$C = R \times \frac{1}{9 \times 10^5} \ \mu\text{f}$$

6. Sphere to sphere (two capacities in series)

$$C = \frac{R}{2} \times \frac{1}{9 \times 10^5} \ \mu\text{f}$$

7. Radial intensity in the dielectric of a metal-sheathed cable

$$N = \frac{V}{r \log \dfrac{b}{a}}$$

The maximum gradient depends on the ratio b/a.

The highest gradient can be shown to be a minimum when

$$b = \epsilon a = 2.72a.$$

Resistivity (ρ) is the resistance per unit volume, usually expressed in ohms per cubic centimeter, or, more briefly, ohm-cm. For most dielectrics flow of current is proportional to the applied potential, but not always, which is to say that some materials, liquids in particular, depart from Ohm's law. Resistivity may decrease with high applied potentials (see Dielectric Constant for range of resistivities).

Conductivity (λ) is the reciprocal of resistivity and is often more convenient to use mathematically.

Absorption.—If potential (direct current) is applied to the electrodes of a condenser with a perfect dielectric (vacuum), there is an initial rush of charging current which then ceases entirely. On discharge, a reverse current flows until the charge is dissipated in the connected circuit and the current ceases. In the case of a dielectric that has a finite resistance, the charging current is augmented by a constant conduction current which though small will persist after the charge is completed. When the source of potential is removed, the conduction current disappears and does not appear in the discharge operation. Many practical dielectrics exhibit still a third current component. When potential is applied, the initial charging current is followed by a decrease of charging current gradually approaching the final conduction current value. The decrease may take seconds, days, or months to arrive at a final value attributable to the conduction of the material. Again, on discharge, the current decreases rapidly at first and then more slowly, gradually approaching zero, and total discharge may take

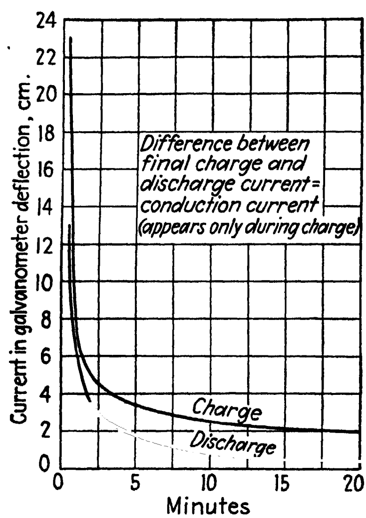


FIG. 1.—Dielectric absorption in composite insulation.

a long time (Fig. 1). Suppose the discharge current is allowed to flow for a time and then the circuit is opened and the condenser allowed to "rest." Now, if a discharge path is again connected, a new discharge current will occur, initially higher than the value attained when the circuit was opened. This will again decrease logarithmically. Such an experiment can often be repeated several times, producing each time a new discharge from an apparently "empty" condenser. This general phenomenon of delayed charge and discharge is known as "absorption." The associated current is called absorption, anomalous, or residual current, and the portion of charge held in the condenser is the residual charge.

Dielectrics may be divided into three classes with respect to absorption behavior.

1. Those showing *no absorption* and exhibiting geometric capacitance in a condenser. These are few in number and are confined to gases and pure solids like sulphur.

2. Those showing *reversible absorption*. They give up their total charge, but over a period of time, sometimes long; *e.g.*, mica, hard rubber. If the difference in amplitude between charge- and discharge-current curves is constant, the absorption current is reversible in character. This difference is the conduction current, which, of course, is absent on discharge.

3. Those showing *irreversible absorption*. They give up on discharge only a portion of the charge. Relatively impure materials or those containing moisture show this characteristic. Irreversible-absorption current (the existence of which is doubted by some) seems to account for some peculiar events. This current during charge approaches a constant value with apparent saturation, and its rate of decay depends on the applied potential. It is observed in some composite solids and many liquids. It is claimed by some to be the result of anomalous behavior of conductivity.

Dielectric Strength.—When subjected to increasing potential stress, a dielectric changes abruptly from an insulator (very small current) to a semiconductor (rapid increase in current), and the dielectric strength or rupturing value for the dielectric under the specific test conditions is said to have been reached. Dielectric strength is not a constant but depends on many factors, such as duration and rate of rise of potential, frequency, temperature,

ambient conditions, thickness of the sample, and physical dimensions of the test apparatus. Failure, called "breakdown" or "puncture," results in an arc and usually destruction of the dielectric at point of failure. Dielectric strength is somewhat analogous to tensile strength.

Dielectric Loss, Defect Angle, Power Factor, Loss Factor.—When subjected to alternating electric stress, dielectrics (particularly solids) exhibit internal losses which result in heating of the dielectric. This was first observed by Siemens in 1864 when he

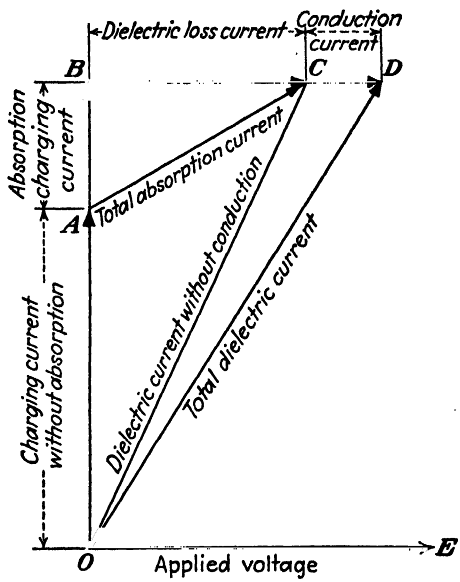


FIG. 2.—Vector diagram of a dielectric.

attempted to use static condensers on alternating circuits. Dielectric loss may be one thousand times as high as the amount accounted for by conductivity and for long duration of stress may be a major factor in the failure of insulation on alternating current. The loss component of condenser current is represented by a vector in phase with the applied voltage, and so the resultant vector of condenser or dielectric current may fail to lead the voltage by the theoretical 90 deg. (Fig. 2). The angular difference from the vector of a perfect condenser is called the "defect angle," which is a measure of dielectric loss. Another measure is the sine of the angle of defect, or the cosine of the angle of lead

of the condenser current, which is designated the "power factor." The tangent of the angle of defect or the angle itself expressed in radians is also substantially the same if the angle of defect is small. DOB = defect angle, DOE = lead angle (Fig. 2).

Loss Factor.—The power factor of a dielectric (cosine of angle of lead or sine of defect angle) is a gauge of the dielectric loss under usual conditions, *i.e.*, when the dielectric constant K remains constant. It is known that K changes with frequency and temperature in some cases, particularly with polar dielectrics. Since the amount of energy stored in a given dielectric is proportional to the dielectric constant K, the product of power factor and dielectric constant is a better measure of dielectric loss. This product is called the "loss factor." More strictly, the loss factor is $K \tan \delta$ (δ is defect angle) but for small angles is nearly equal to $K \cos \theta$ (θ is angle of lead). When dielectrics to be employed in capacitors are compared, loss factor is an important criterion. Although a high dielectric constant is desired, the corresponding power factor must be low if losses are to be kept within reasonable limits.

CHAPTER II

THEORIES OF DIELECTRIC BEHAVIOR

The brief summary in Chap. I describing and defining the major terminology applied to dielectrics did not attempt any explanation of causes or means. Doubtless the reader has made mental reservations and has asked why dielectrics act as described. We shall attempt therefore to summarize here the more important theories evolved by a long line of scientists, starting with Maxwell. After we have rejected hypotheses that cannot be demonstrated and sifted out the more fantastic results of writers more interested in mathematical stunts than physical facts, certain useful correlations can be given which represent a fairly consistent concept of dielectric phenomena.

The various characteristics of dielectrics may be grouped around four fundamental phenomena, *viz.*, *polarization*, *absorption*, *loss*, and *breakdown*. Innumerable theories have been evolved to explain the observable facts related to such phenomena, some plausible and some fantastic; but none completely satisfying. There have been trends away from ideas proposed and then back toward them. For example, Maxwell's conception of the two-layer dielectric was discarded and later revived. It still does very well in explaining absorption, although it falls down in some cases of behavior, as do the other theories. We must conclude, after examining the theories of eminent scientists, that our progress in explaining dielectric phenomena has been discouragingly slow and that the sum total of our knowledge is meager. Much factual material has been collected, but the underlying and connecting fabric of theory is fragmentary. It is known that moisture in dielectrics is beneficial under some conditions with some materials, but highly detrimental under the same conditions with other materials. Why? "Anomalies of conduction" is the convenient phrase we use when we really do not know the answer. Consequently, a discussion of theories may not be very reassuring, but it will show the development of ideas and the extent of effort that has been expended in this field.

Polarization.—This phenomenon occurs when the "center of gravity" of positive charges is at a different point from the position of the centroid of negative charges. Surface charges of opposite sign appear on opposite faces of a dielectric in which this takes place, and the material is said to be "polarized." In the simplest case, if two equal and opposite point charges are displaced a small distance from each other, we have a dipole. In Fig. 3 the potential V at point P is

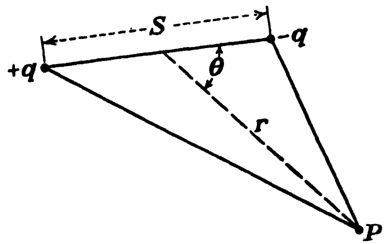


FIG. 3.—Polar moment of a dipole.

$$V = \frac{qS \cos \theta}{r^2}$$

and qS is the electric moment of the dipole. Dielectrics that show this effect without an external electric field are called "polar substances" or materials having polar molecules. The usual way of telling whether or not a dielectric is polar is to measure the dielectric constant under different conditions. K for polar molecules changes with temperature, field strength, or frequency, perhaps with all three.

A single type of polarization seems insufficient for complete explanation of dielectric phenomena, particularly the anomalous dispersion or change of dielectric constant with frequency. Morgan and Murphy[1] have presented a systematic classification of several theories that helps to clear up many difficulties. The four types of polarization that occur in dielectrics are

1. Electronic polarization.
2. Atomic polarization.

(Types 1 and 2 form and disappear rapidly, in periods of time less than 10^{-10} sec. and are known as "instantaneous polarizations.")

3. Dipole polarization.
4. Interfacial polarization.

(Types 3 and 4 take longer to occur, given rise to absorption effects, and are therefore known as "absorption polarizations."

[1] *Bell System Tech. Jour.*, vol. 16, p. 493, 1937.

In alternating fields, they may take longer than one alternation (half cycle) to form. The absorption effect, therefore, is more pronounced as the frequency is raised.)

Let us note the characteristic nature of each of these four.

1. *Electronic polarization* is due to displacement of electrons with respect to positive nuclei *within the atom.* Polarizability of various gases, for example, is different and is dependent on number of electrons and the binding force. Hydrogen, a molecular gas, has 2 electrons per molecule. Helium, an atomic gas, has 2 electrons per atom. But, for the same number of electrons per unit volume, hydrogen has four times the susceptibility of helium. This means that the hydrogen electrons are less tightly bound and are more easily polarized. With some materials (*e.g.*, benzene), electronic polarization is the only one present, and consequently the dielectric constant is a constant throughout electrical range of frequencies. Electronic polarization occurs up to visible light frequencies.

2. *Atomic polarization* is due to displacement of charged atoms with respect to each other in the *molecule.* This type of polarization takes place up to infrared frequencies (10^{14} cycles per second) and is usually measured by taking the total polarization at infrared frequency and subtracting the polarization measured at visible frequencies (electronic polarization).

3. *Dipole polarization* is due to the effect of the applied fields on the orientation of molecules having a *permanent dipole moment.* This is an absorption type, occurring in the electric frequency range. In substances where the charges are symmetrical, no dipole results. There are probably more polar substances (having permanent dipoles) than nonpolar. The atomic structure of a substance will usually show whether it is polar or not; or, conversely, if the substance is known to be polar (exhibiting unusually high dielectric constant, for example), something of its structure may be inferred.

Water might be thought to be symmetrical, H—O—H, but this is not the arrangement. It is $\mathrm{O}\Big\langle{}^{\mathrm{H}}_{\mathrm{H}}$, which is unsymmetrical. Water is highly polar and has a high dielectric constant (80). Dipole polarization contributes to the dielectric constant only in the electric frequency range. Certain chemical substances

or radicals are nonpolar: H_2, N_2, O_2, CH_4, CCl_4, C_6H_6. The following polar radicals are arranged in decreasing order of polar moments: NO_2, CN, CO, OH, NH_2, Cl, Br, I, CH_3. In the light of this series, we can account for the dielectric constants of the following liquids:

Compound	K	Cause for value of K
Nitrobenzene ($C_6H_5NO_2$)	34	NO_2 radical has high polar moment
Chlorobenzene (C_6H_5Cl)	5.5	Cl radical has lower polar moment
Methyl benzene ($C_6H_5CH_3$)	2.8	CH_3 radical has weak polar moment
Benzene (C_6H_6)	2.3	C_6H_6 is nonpolar

4. *Interfacial* (or ionic) *polarization* is due to the accumulation of free ions at the interfaces between components of a heterogeneous solid material. Compounds or laminated materials usually

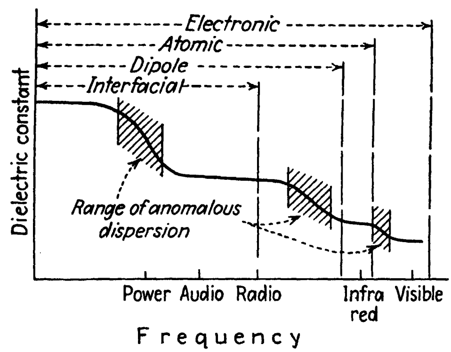


FIG. 4.—Polarization regions.

have components with differing conductivities and constants. At the boundaries, interfacial polarization takes place. Impregnated paper and laminated plastics are common examples. The dielectric constant of cellulose is affected by the interfacial polarization due to water and dissolved salts in the structure. Interfacial polarization occurs up to radio frequencies and is important in diathermy.

Any band of frequencies in which dielectric constant decreases with increasing frequency because of inability of polarization to be completed during a cycle is called a region of absorption or of "anomalous dispersion." It may occur in more than one frequency range (Fig. 4).

Effect of Temperature on Polarization.

1. Electronic polarization is independent of temperature.

2. Atomic polarization has small positive temperature coefficient.

3. Dipole polarization has negative temperature coefficient.

4. For interfacial polarization, the effect of temperature is not known.

Absorption.—This phenomenon, described in Chap. I, is considered by many physicists to be an abnormal property, something that violates classical equations and that must be explained by anomalies in some inherent factor, such as atomic structure. If this viewpoint is taken, all dielectrics ordinarily used are abnormal and the abnormal is normal. Most of the theories advanced to explain dielectric absorption leave much to be desired and do not arrive at the fundamentals of cause and effect. They merely explain phenomena in terms of commonly accepted (but not proved) concepts. We may compare this method with attempts to explain the sunrise. An adult is satisfied if one says the sun appears to rise each day because the earth is rotating, so that periodically a given point on the surface turns toward the sun, but that the sun does not move around the earth. To the small boy this is only the start. What makes the earth turn? Why does the earth encircle the sun? Why is the sun a source of light, and not the earth? What makes the sun so hot? And so on. Thus we can explain many dielectric phenomena by relations of electric force, permittivity, conduction, energy, and charge and thereby push the inquiry back a step at a time; but in so doing we raise more questions than we answer. J. B. Whitehead[1] states the facts as follows:

Even the simplest natural phenomena leave us groping when we seek their ultimate understanding as a sequence of cause and effect. If we pursue our effort to understand the nature of each cause, we soon come to the limit of our exact knowledge and are led into the realm of metaphysical speculation. For the most part, in the field of physical phenomena, we are usually content if we can express them in terms of the fundamental mechanical relations of force, mass, motion, and energy. In our human make-up we are conscious of the effects of these relations, we react to them each hour of the day, and we have set up

[1] "Lectures on Dielectric Theory and Insulation," p. 48, McGraw-Hill Book Company, Inc., New York, 1927.

units and methods for their measurement. Consequently they are accepted as foundation stones upon which we can erect the structures of theories accounting for more complex natural phenomena. Thus the tendency and effort of modern physics is to explain all natural phenomena in terms of molecular, atomic, and subatomic masses and motion. Explanations and theories are thus relative terms only, and we are usually satisfied to consider that we have a theory of any new natural phenomenon, if we can explain it in terms of more fundamental phenomena whose laws are well recognized, even though they may not themselves be completely understood. Thus, since the earliest discoveries of the properties of dielectrics, many explanations of their origin and nature have been suggested. Few if any of these suggestions, however, have risen to the dignity of a theory substantiated by quantitative experimental test.

The explanations of absorption fall into four groups: (1) unusual atomic structure; (2) electron movements within the atom; (3) changes in polarization; (4) changes in conductivity, including electrolytic and moisture effects.

1. *Structure.*—Maxwell's theory of dielectric absorption has merit because it is simple, relies on existing laws, and explains a large body of experimental facts. It belongs to the structural theories. He considered a dielectric as having a capacitance and conductance functioning independently but concurrently. Absorption would then be attributed to the appearance of conducting areas or layers in the dielectric. Or if a dielectric is a composite of particles of different conductivities and dielectric constants, absorption can be explained. A truly homogeneous material would then show no residual charge. Experimental confirming evidence is not quantitative in nature, and the conductivity idea is hardly sufficient to account for absorption as found in some substances. For example, some pure substances exhibit absorption wholly disproportionate to any possible conducting impurities. Then again, some liquids, surely containing components of different K and λ, show no absorption. Wagner prefers to imagine dielectrics with no conductivity but containing small embedded conducting spheres. His conclusions agree with Maxwell's. Von Schweidler conceived absorption as a variable form of polarization (mathematically represented by a series of polarization terms), which he claimed resulted from high-frequency oscillations of charges, damped aperiodically.

To fit his explanation, we have to assume different kinds of molecules (at least three) in the same substance. So far, no one has demonstrated the existence of these varieties of similar molecules.

It is interesting to examine Maxwell's reasoning in the simple "two-layer dielectric" case, as an explanation of the origin of absorption in anomalies of structure. Assume two equal-thickness dielectric layers of different dielectric constants K_1 and K_2 and different conductivities λ_1 and λ_2, respectively. When potential is applied to electrodes at the faces, the potential gradients g_1 and g_2 are inversely proportional to the dielectric

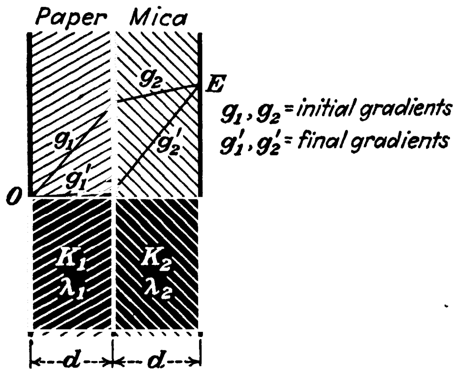


FIG. 5.—Maxwell's two-layer dielectric.

constants K_1 and K_2. On the other hand, the conduction current that flows establishes a different gradient, inversely proportional to conductivities λ_1 and λ_2, that may have a ratio quite different from K_1 and K_2. Maxwell states that this dual-gradient condition produces a charge collected on the surface where the two layers join. The initial collected charge ultimately is distributed so that the final gradients are determined by the conductivities. The temporary charge on the interfacial surface is the absorbed charge, and the current change that takes place in the transition from a gradient based on K to one based on λ is the characteristic absorption current (Fig. 5).

Wagner illustrates Maxwell's concept by an example.[1] Assume a two-layer dielectric consisting of impregnated paper ($K_1 = 2$,

[1] Adapted from J. B. Whitehead, "Lectures on Dielectric Theory and Insulation," McGraw-Hill Book Company, Inc., New York, 1927.

$\lambda_1 = 10^{-11}$) and mica ($K_2 = 8$, $\lambda_2 = 10^{-15}$) equal in thickness d. The displacement is the same in both layers.

Since $D = KE$ and E is the same in numerical value as the gradient,

$$D_1 = K_1 g_1 = D_2 = K_2 g_2. \tag{1}$$

The total potential applied initially (V) is the sum of gradient times thickness of layer 1 plus the same product of layer 2, or

$$g_1 d + g_2 d = V \qquad (g_1 \text{ is initial gradient in layer 1}) \tag{2}$$

Combining (1) and (2), we solve for g_1 and g_2

$$g_1 = \frac{V}{d} - g_2. \qquad g^2 = \frac{K_1 g_1}{K_2}$$

Therefore,

$$g_1 = \frac{V}{d} - \frac{K_1 g_1}{K_2}.$$

But from (2)

$$g_1 + g_2 = \frac{V}{d}.$$

Therefore,

$$g_1 + \frac{K_1 g_1}{K_2} = \frac{V}{d}.$$

Multiplying each term by K_2, we have

$$K_2 g_1 + K_1 g_1 = \frac{(VK_2)}{d}$$

Then

$$g_1 = \frac{VK_2}{d(K_2 + K_1)}. \tag{3}$$

By similar operations,

$$g_2 = \frac{VK_1}{d(K_2 + K_1)}. \tag{4}$$

These two expressions will represent the initial gradients dependent on dielectric constant. Substituting values, we find the paper assumes 80 per cent of the applied potential and the mica 20 per cent.

$$g_1 = \frac{V \times 8}{d(8+2)} = 0.8\,\frac{V}{d}.$$

Now consider the final state in which the gradients will be proportional to the reciprocal of conductivities. The current is the same through both layers. Then the current in one layer is

$$g_1'\lambda_1 = g_2'\lambda_2 \qquad (g_1' \text{ is final gradient in layer 1})$$

and

$$g_1'd + g_2'd = V.$$

By methods similar to those used in deriving the initial gradients g_1 and g_2, the final gradients g_1' and g_2' can be developed. Then,

$$g_1' = \frac{V\lambda_2}{d(\lambda_2 + \lambda_1)}, \tag{5}$$

$$g_2' = \frac{V\lambda_1}{d(\lambda_2 + \lambda_1)}. \tag{6}$$

In this case the potential division is 0.01 per cent on the paper and 99.99 per cent on the mica.

$$g_1' = \frac{10^{-15}}{10^{-15} \times 10^{-11}}\,\frac{V}{d} = \text{approximately } 10^{-4}\,\frac{V}{d}.$$

Returning to the displacement $(K_1g_1 = K_2g_2)$, the initial displacement equals $2 \times 0.8V/d = 1.6V/d$. The final displacement is not the same in the two layers, and the difference is a matter of absorption. Then $K_2g_2' - K_1g_1'$ will show the absorption.

$$8 \times 0.9999\,\frac{V}{d} - 2 \times 0.0001\,\frac{V}{d} = 7.99997\,\frac{V}{d}.$$

The difference in displacements (absorbed charge) is five times the initial displacement, and the capacitance calculated on this basis is therefore five times the geometric capacity.

2. *Electron Motion.*—Electron motion is called by several authors a clue to absorption. These theories have sprung up with the increase in knowledge of the electronic nature of matter. Decombe noticed that there is a definite relation between mechanical and electrical phenomena. Motion in a magnetic field producing an electromotive force, thermoelectric effects, and electrical effects of pressure on piezocrystals, are examples.

Thus, motion of the electron within the atom or deformation of the atom may then cause changes that give the absorption effect. Our concern is then what causes the motion, not the same in all materials. We must assume that this is a property of the particular kind of atom, and the more homogeneous the material the less it is subject to atom deformation or electron disturbances. But this is not a very satisfactory answer, for we do not know much more than we did before. Still, the idea of anomalies of electron behavior seems plausible, and more may be learned in the future.

3. *Changes in Polarization.* The previous history of a dielectric determines its behavior at any moment. The Hopkinson principle of *superposition* states that the effects of past and present polarization are independent of each other and are superposed to determine the present state. Expressed another way, Hopkinson proposed that the actual displacement at any time (t) is made up of the instantaneous displacement KE and another quantity composed of the residual effects of earlier values of E which have been varying with elapsed time. The varying rates of decay of previous displacements account for absorption phenomena. Another author, M. H. Pellat, also proposed an initial constant polarization and a superposed polarization varying with time. His mathematical expression differs from Hopkinson's, but the idea is similar. Neither offers an explanation of the mechanism of the process.

Displacement that is influenced by the motion of charges in a viscous medium has been advanced as an explanation. Some imagine molecules with an elastic ether surrounding them which is displaced when an electric field is applied. If displacement of the medium is instantaneous (as in a perfect dielectric), absorption is absent; but in most dielectrics it is supposed the molecules are displaced with a viscous motion, and this is the cause of absorption.

Dielectric hysteresis has been proposed by many (after work by Steinmetz) to explain the absorption effect and its attendant loss under alternating stress. There is much to recommend the term, since many other characteristics of dielectrics are analogous to those in magnetic material and in mechanical systems. We have already noted several analogies between electrostatic and electromagnetic expressions, and we find also that hysteresis

loops can be obtained, measuring the polarization resulting from a cyclic variation of field intensity.

However, objections to this designation are also valid. The name, though usefully descriptive, is not accurate. Two of many arguments offered against its use are: (1) No saturation phenomenon is found in the dielectric case. (2) Displacement eventually is proportional to intensity, whether rising or falling, the lag being only temporary, whereas magnetic hysteresis is present no matter how slowly the magnetizing force is changed.

4. *Changes in Conductivity.*—Unexpected variations in conductivity may be plausibly proposed as a cause of absorption. It is known that gases and liquids do not always follow Ohm's law. Conduction falls below true proportionality with increasing electric field, up to a certain point near breakdown, and then increases faster than the applied potential. In both gases and liquids, it is assumed that the ions are drained to the electrodes more rapidly at higher stress (below breakdown) and the conduction current decreases. Gases and liquids (of high resistivity) exhibit a current-saturation effect with increasing potential. Glass behaves as an electrolyte and has ionic conduction, especially when hot. Moisture produces some peculiar effects on conductivity. As Evershed demonstrated with his glass-tube model, moisture in a filament of insulation will collect in globules in a weak field, increasing the resistivity, whereas in a strong electric field the drops are spread or stretched into thin continuous films on the walls of the filament and the conductivity is increased. These points of evidence and many others seem sufficiently anomalous and unexplained to be considered as possible causes of absorption.

Continuous variation of both conductivity and dielectric constant through the medium, from one electrode to the other, is the conclusion of Anderson and Keane. They claim also that conductivity depends on electron density, and residual charges arise from surface-resistance variation with time.

Joffé[1] tries to save the validity of Ohm's law by adding a term for counter electromotive force of polarization. His theory is applicable at least to crystals and glass, in which it seems reasonable to suppose that ions are set free in the dielectric, con-

[1] "Physics of Crystals," McGraw-Hill Book Company, Inc., New York, 1928.

sidered as an electrolyte. These freed ions cause space charges and a polarization potential. Ohm's law then becomes

$$E - e_p = RI,$$

where e_p is the polarization voltage which varies with current and time, finally arriving at a fixed value. The confirming evidence was derived from studies on calcite, slate, and stone.

Dielectric Loss.—This is the resultant sum of losses arising on alternating potentials from absorption, and conduction loss. Any known dielectric, except a gas, has appreciable conduction current, accounting for a small energy loss in the dielectric, even if there is no absorption. A dielectric with conduction loss only would show no change in capacitance with increase in frequency. In solids, the component of energy loss due to absorption is usually much larger than the conduction loss, which may be only 1 per cent of the total.

The theories (many of them originally developed to explain absorption on direct current) that seem most useful in explaining dielectric loss are based on

1. Nonhomogeneity of structure (*e.g.*, Maxwell's two-layer dielectric).
2. Molecular action (damped oscillations).
3. Free ions moving within the dielectric (electrolytic behavior).
4. Dipole phenomena (explain losses in liquid dielectrics).

The close causal relation between direct-current absorption and alternating-current loss is borne out by the possibility of calculating losses or predicting them from knowledge of the anomalous or absorption currents. If, in a condenser circuit to which direct-current potential is applied, the instantaneous values of current are measured and compared with the instantaneous values of theoretical charging current calculated from the circuit constants (taking into account also the dielectric conduction current), the difference between the two curves is the anomalous current. If this anomalous or absorption current is used in calculating loss on alternating current, the results agree well with measured loss.

Several authors have tried to find causes other than absorption which could contribute to dielectric loss and have concluded that no other source is discernible or necessary to account for behavior. Theories of absorption on direct potentials can be extended to

the alternating case, usually with some modification of mathematical terms. One puzzling disagreement has come to light in comparing the conclusions deduced from various theories. For some concepts the dielectric loss per cycle must be independent of frequency; for others, loss per cycle should vary inversely as the frequency; for still others the loss per cycle ought to be proportional to frequency. K. W. Wagner[1] attempted to reconcile these views with some success by introducing an absorption constant h, defined as

$$h = \frac{K_1\lambda_2 - K_2\lambda_1}{K_1K_2(\lambda_1 + \lambda_2)}.$$

Assuming a two-layer dielectric of differing dielectric constants and conductivities, the dielectric loss depends on a function of h, *viz.*:

$$h\frac{\omega t}{1 + h\omega^2 t^2}.$$

Plotting loss against frequency, we obtain a form of curve (Fig. 6) that has a rising front, a maximum at frequency of $\sqrt{1+h}$, and a decreasing tail approaching an asymptote. Thereby, by a proper choice of frequency, one can subscribe to any of the three laws of the effect of frequency on losses. Addenbroke found that very good insulators, such as glass and gutta-percha, have losses proportional to frequency. They must therefore fall on the rising part of the curve, and the crest must be beyond any frequency used in the tests. It was found that moist insulation seems to have loss independent of frequency. The conclusion here is that the crest of the curve must be broad and include a wide range of frequencies.

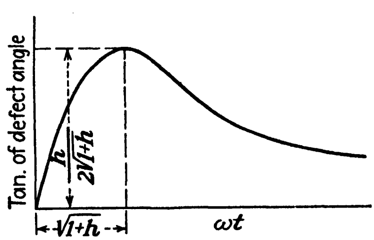


FIG. 6.—Effect of frequency on loss. Wagner's absorption constant h.

Dielectric Breakdown.—This is a very important property of insulating materials, probably more indicative of useful quality than any other single criterion. Rapid loss of insulating value occurs at breakdown, which means that current conduction

[1] WHITEHEAD, *op. cit.*

suddenly increases. The mechanism by which this happens is very incompletely known. Many theories have been developed, most of which account for some facts; but no universal law has emerged. We are now beginning to think that probably breakdown is not a simple, single phenomenon but has several characteristic forms.

Electric failure in gases, where the molecules are relatively far apart, is reasonably well outlined in theory. There is no appreciable conduction or absorption to complicate matters, and breakdown seems to occur at definite gradients in a consistent manner, adequately explained by motion of electrons in the field and ionization by collision. Electrons striking neutral gas atoms release the charges that have previously been balanced, and new charged particles are accelerated by the field, knocking out still more charges, all building up cumulatively until current flows. For certain limited conditions, Paschen's law of breakdown in gases holds. This formula (first stated 50 years ago) expresses the relation that breakdown of any gas is proportional to the product of breakdown distance and pressure. There seem to be no vast regions of knowledge to explore in respect to gas behavior, which is something we cannot claim in connection with liquid and solid dielectric breakdown.

Some authors have attempted to consider liquids as highly compressed gases, but application of Paschen's law in the pressure regions required to form liquids from gases does not check with experimental fact. The dielectric strength of liquids is not so high as might be expected in comparison with gases. Liquids differ among themselves in performance, depending on atomic structure. It is known, for example, that pure hydrocarbons have high breakdown but combinations of hydrocarbons with oxygen show greatly reduced dielectric strength. Many liquid dielectrics have electrolytic characteristics, and the motion of ions through the medium may cause progressive ionic breakdown. An electric field can produce dissociation in certain liquids, particularly over a period of time, resulting in conducting compounds not existing in the unstressed liquid. The familiar phenomenon of the formation of a waxy compound in oil-filled cables after long stress is an example of chemical change.

Solid dielectric breakdown is even more complex and not readily explained in consistent terms. Physically, we know

what happens. At a critical gradient the current suddenly increases and punctures or burns the sample locally. Apparently, a cumulative instability phenomenon has taken place which rapidly destroys the dielectric.

Any theory advanced must give a reason for the assumed motion of electrons in a viscous medium, such as a solid. Sudden conduction must be caused by some releasing of electrons from their nuclei or an upsetting of the balanced arrangement of groups of charges in a polarized molecule. But how are these bonds broken? The insulating properties of some crystals (*e.g.*, salt) disappear if the crystal structure is destroyed. If an electric field can rupture the lattice structure of a crystal, a phenomenon analogous to mechanical rupture when elastic limits are exceeded, conduction can be imagined. Another point of view illustrated by some theories is based on the thermal effect. Electric stress produces energy loss by conduction, at least, and by conduction and absorption in many substances. If the rate of heat dissipation is too low, the dielectric temperature rises. The bonds between electrons and nuclei and between ions are greatly weakened by increase in temperature. We know, for example, that if the temperature is high enough we have thermionic emission, which means that the electrons are easily dislodged and are free to move. These preliminary suggestions lead us directly to a discussion of the major theories of dielectric breakdown. They fall into three classes:

1. Thermal theories: Internal losses cause progressive instability, followed by breakdown.
2. Ionic theories: Dissociation similar to electrolytic behavior causes conduction leading to failure.
3. Disruptive theories: Stress causes release of electrons by exceeding their "tensile" strength.

1. *Thermal Theories.*—The most completely developed thermal theory is that of Wagner.[1] His essential contributions can be summarized as follows.

All solid dielectrics are considered to be somewhat heterogeneous. Some spots, layers, or filaments are lower in resistance than others. The current distribution over the specimen is therefore not uniform when potential is applied. The weak

[1] "Physical Nature of Breakdown of Solid Dielectrics," *A.I.E.E.*, vol. 41, p. 288, 1922.

portion carries more current, and the energy released heats the spot. If the heat is conducted away, either by the insulation or by the electrodes, nothing happens and the condition is stable. But if the heat is not removed fast enough, the weak spot becomes

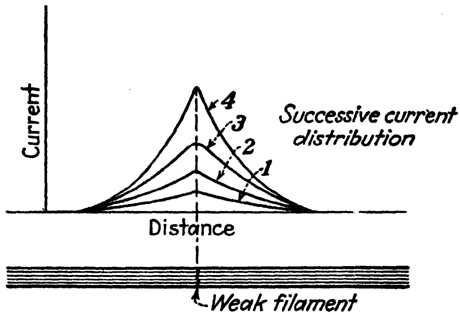


FIG. 7.—Wagner's weak filament breakdown.

hotter and lower in resistance, since most materials have a negative temperature coefficient of resistance. This goes on in a cumulative manner, until thermal instability results, followed by breakdown. Electric strength decreases with increasing temperature, and breakdown occurs when the lowering of strength

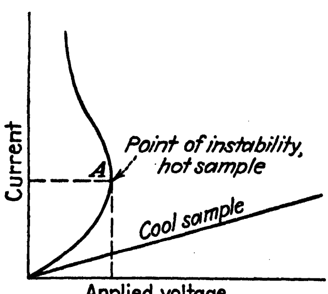


FIG. 8.—Volt-ampere characteristic of insulation. (*Wagner.*)

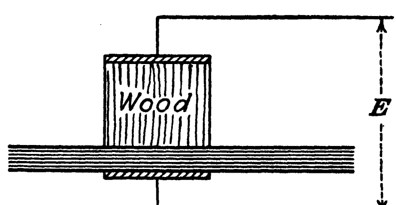


FIG. 9.—Wagner's method for obtaining volt-ampere characteristic of insulation.

of the heated dielectric matches the applied potential. In the weak spot, it is conceivable that thermionic conduction is finally reached. Figure 7 indicates Wagner's picture of progressive stages (1, 2, 3, 4) in the unbalanced current distribution. The volt-ampere characteristic of a dielectric may be illustrated by Fig. 8, showing the lower straight curve for a cool specimen and the upper curve for a heated sample. Beyond point A, instabil-

ity is evident. It is of interest to learn how Wagner got the curve of Fig. 8 without passing to breakdown. He used wooden electrodes (grain parallel to current flow) (Fig. 9) that had lower resistance *with* the grain than *across* the grain. In this way, he limited the current and prevented complete destruction of the dielectric. There was no concentration of energy, at the weak point, such as would have existed if a metal electrode had short-circuited all the elements of the dielectric at the surface and fed into the weak spot the energy of the condenser thus formed.

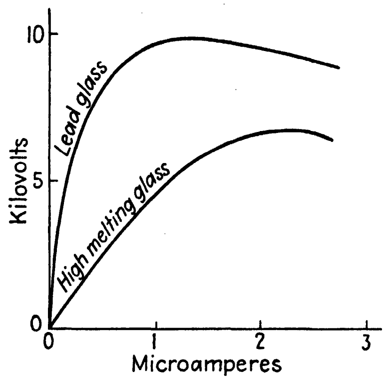


FIG. 10.—Volt-ampere curves of glass (*Wagner.*)

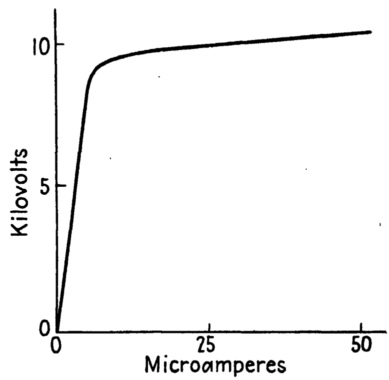


FIG. 11.—Volt-ampere curve of mica. (*Wagner.*)

Several materials were tested to show the point of instability. Figure 10 shows the different inflection point for two kinds of glass. Figure 11 for mica shows that the turning point is much beyond the limits of the test. The weak filament must change its resistance with temperature according to some reasonable function. Wagner offered three possible forms:

1. Resistance decreases with increasing temperature but does not vanish at finite values of temperature.

$$R = R_0\epsilon^{-\alpha\theta}$$

where R = resistance of filament at temperature rise θ.
R_0 = initial resistance at temperature $\theta = 0$.
α = constant, usually 1 or greater.
θ = temperature rise of filament above remainder.

2. Resistance vanishes at temperature called "burning temperature."

$$R = R_0\left(1 - \frac{\theta}{T}\right).$$

where T is a constant.

3. Resistance decreases continuously with increase in temperature.

$$R = R_0\left(\frac{T}{T + \theta}\right)^{\alpha}.$$

The third expression seems to fit most dielectrics best.

Wagner's conception centers in a conducting filament or weak spot. Other thermal theories have been proposed by Rogowski, Meyer, and others that do not require this factor. They develop relations of thermal instability that are general and include homogeneous materials. A progressive change in resistance with increase in applied voltage is Rogowski's[1] explanation, but he does not give a reason for such behavior.

2. *Ionic Theories.*—If we conceive of solid dielectrics as electrolytes in which ions move to give a current, the source of such continuous supplies of ions must be sought. High temperature might give such a result, but at ordinary levels we must look to ionization either by collision or by chemical action initiated by the electric field. If ions are present in a solid dielectric, they should move proportionately to the field strength, and current will follow Ohm's law, at least at low intensities. In gases, if the field were increased we should approach a saturation level where current did not increase as fast as the potential; but in solids this phenomenon is rare. With still higher fields, it would be expected that fast-moving ions will produce other particles at an increasing rate until instability occurs.

Joffé[2] assumes a critical ionic density necessary to account for breakdown. Failure is an eventual result of exceeding the critical point.

Hoover[3] explains ionic failure as an upset in equilibrium. Ions are continually being formed by electrons leaving molecules, and at the same time other ions are being neutralized by joining molecules. When a medium is polarized in a field, ions may take on sufficient velocity to destroy the balanced "birth and death," so that rupture current occurs.

[1] *Arch. Elektrotech.*, vol. 2, p. 155, 1924

[2] *Op. cit.*

[3] *A.I.E.E.*, vol. 45, p. 983, 1926.

3. *Disruptive Theories.*—Analogies based on mechanical phenomena always have an appeal, for they involve tangible things familiar in our experience. We therefore have to be on guard that the analogy is not carried too far. The general proposition of imagining electric breakdown to be a sort of rupture and destruction of molecular and other bonds in the material seems to have considerable merit. We know that breakdown of dielectrics at low temperatures, in very thin specimens and with impulse potentials, cannot be explained by thermal theories. Evidence is available to support the disruptive explanation. Materials with stable molecular structure (for example, the simple substances having low atomic weight and low number of electron orbits) seem to have high dielectric strength. Those with an "attenuated" system should be vulnerable to forces that could break the bonds. This contention is roughly true. Following this line of argument, materials of high atomic weight should be poor insulators, a statement that is relatively true, in gases at least. Many more correlations between structure and electrical properties could be cited, strengthening the disruptive-breakdown case. Another line of confirmation is the effect of mechanical stress on electric breakdown. Weicker[1] observed a reduction of breakdown to 10 per cent of the normal value when mechanical stress approaching the elastic limit was applied. Cracks in crystalline substances seriously affect breakdown. It is common experience that repeated stresses have a cumulative effect on the "life" of insulation. Clark[2] and numerous others have investigated the deteriorating effect or fatigue phenomenon in insulation, which seems to be quite similar to mechanical fatigue in decreasing the strength.

Summarizing the three types of theories of dielectric breakdown, the following statements will permit ready comparison.

Cardinal Points in Solid Dielectric-breakdown Theories

1. Thermal:
   a. Thermal instability leads to breakdown.
   b. Below failure, heat dissipation must be greater than heat generation.
   c. Conditions of heat conductivity or flow are important.

[1] *ETZ*, 1926, p. 177.
[2] *A.I.E.E.*, vol. 44, p. 158, 1925.

d. Alternating-current and direct-current thermal breakdowns are similar.
e. If conditions are not conducive to thermal breakdown, breakdown may occur in other ways (disruptive or ionic).
f. Thick, poorly cooled samples follow thermal breakdown.

2. Ionic:
a. Ionization behavior depends on voltage.
b. Movement of ions dissipates energy.
c. Chemical dissociation causes bubbles and decomposition, leading to failure.
d. Upset of ionization balance leads to failure, as upset of thermal balance leads to failure.

3. Disruptive:
a. Analogous to mechanical tensile strength.
b. Electron bonds in atoms affect breakdown. Valence electrons are most easily detachable.
c. Some simple molecules have stable atoms and are better insulators.
d. Bonds or stability of structure in crystals may determine their dielectric properties. Salt as crystal is insulator but as Na and Cl is a conductor.
e. Mechanical stress superimposed lowers breakdown.
f. Mechanical fatigue and electrical fatigue are shown analogous.

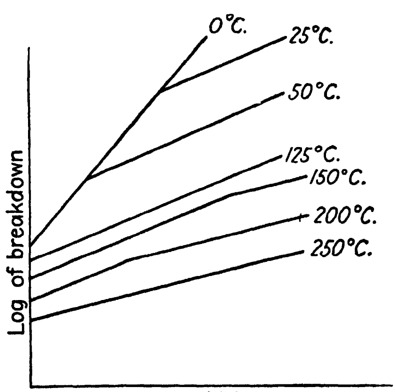


FIG. 12.—Three breakdown regions for lead glass. (*Moon and Norcross.*)

Combinations.—Are the three classes of breakdown theories incompatible? Apparently, there is ample proof that each may

be demonstrated for certain limited conditions. A remarkable addition was made to our knowledge by Moon and Norcross[1] who showed experimentally that all three can take place in the same material. These authors described the "three regions" of dielectric breakdown. Glass seems to be a material that shows the three kinds of breakdown most effectively (Figs. 12, 13). For

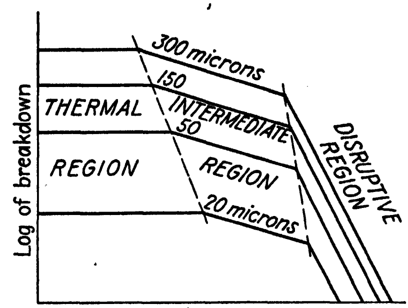


FIG. 13.—Three breakdown regions for lead glass. (*Moon and Norcross.*)

a lead glass known as G-1, and used in electric lamp bulbs, the three regions were:

Type	Temperature, °C.	Breakdown temperature relation	Breakdown thickness relation
Disruptive. . .	0	Independent of temperature	Breakdown $= k_1 \times$ thickness
Ionic.	50 to 125	Exponentially as reciprocal of absolute temperature	Breakdown $= k_2 \times th^{2/3}$
Thermal.	250 to 300	Rapidly with temperature	Breakdown $= k_3 \times th^{1/4 \text{ to } 1/2}$ k_1, k_2, k_3 are constants

A wider intermediate or ionic region was shown by lime glass than by lead glass. In the disruptive region, soda-lime glass is best, but it is worse in the other two regions than lead glass. Mica was tested, and the thermal breakdown region was not yet reached at 500°C. Mica, therefore, usually has a disruptive breakdown and a straight-line relation between thickness and breakdown at usual temperatures of application.

[1] *A.I.E.E.*, vol. 49, p. 755, 1930.

An interesting comparison of the three types of breakdown expressed in kilovolts per centimeter for various materials is given by Moon and Norcross.

Material	Disruptive	Ionic	Thermal	First transformation temperature, °C	Second transformation temperature, °C
Fused quartz	5,000	1,815	560	− 31	270
Pyrex	4,800	1,050	200	− 20	140
G-1 glass	3,100	1,200	102	+ 22	150
Cover glass	......	730	60	+ 20	165
Lime glass	4,500	355	32	− 33	217
Celluloid (125)	2,500	420	...	− 10	140
India ruby mica	10,600	.....	...	+100	

CHAPTER III

FACTORS AFFECTING DIELECTRIC BEHAVIOR

Time.—Most dielectrics will withstand a higher voltage for a short time than for a prolonged interval. Or we may say that each material has a time-voltage characteristic curve which expresses the relation between breakdown voltage and the time at that voltage to produce breakdown. For each dielectric, there is a minimum breakdown voltage that is approached asymptotically as the time of application of that voltage

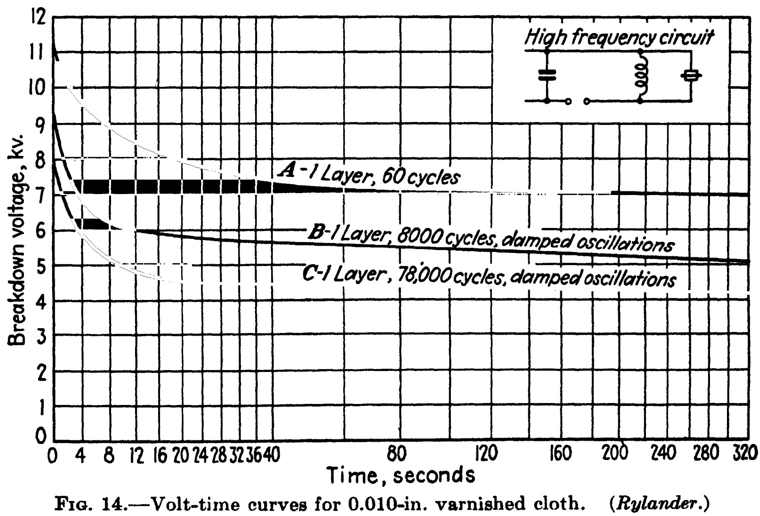


FIG. 14.—Volt-time curves for 0.010-in. varnished cloth. (*Rylander*.)

approaches infinity; and, for each value of potential above that minimum, there is a finite time required for breakdown. As might be expected, the shape of the curve representing breakdown vs. time is exponential, rising rapidly for short times, when plotted on rectangular coordinates (Fig. 14).

Some materials exhibit exceptionally high breakdown for short-time application of voltage, particularly under impulse test, but fail at much lower voltage applied for minutes or hours. There

seems to be a wide difference in the behavior of materials, and very little predicting can be done, a fact that might be inferred from the variation in nature of breakdown noted in the discussion of causes of breakdown. Short-time failures may be due to wholly disruptive factors, whereas long-time failures may involve other causes. It is known that: (1) Extended stress application produces heating, with accompanying lower resistance, leading to thermal destruction of the material; (2) time increases electrolytic ionization leading to breakdown of some substances; and (3) local ionization of air (corona) in or around the dielectric deteriorates insulation if continued long enough. Corona damage is due partly to nitrous oxide produced (which, in the presence of moisture, gives nitric acid) and partly to rapid oxidation from ozone also produced by corona. From these inferences reinforced by observations of behavior, we gather that in long-time breakdowns many deleterious elements are combined, making a complex situation.

Many attempts have been made to express the time-voltage relation mathematically, so that all variables may be covered; but most formulas hold only for limited conditions. The simplest and most useful is that of F. W. Peek, Jr.,[1] who stated that $V = V_0 + aT^{-1/4}$, where V is breakdown voltage at any chosen time, V_0 is the minimum- or infinite-time breakdown, a is a constant, and T is time. If we plot V against $T^{-1/4}$, the graphical representation is a straight line from which two important facts can be obtained. If two values are known, the slope of the curve can be drawn, and the intercept at $T^{-1/4} = 0$ is the infinite-time breakdown. The slope of the line a might be termed the deterioration factor (Fig. 15). Unfortunately, Peek's law holds for only limited cases. At long times for very good dielectrics and for dielectrics that behave erratically the law

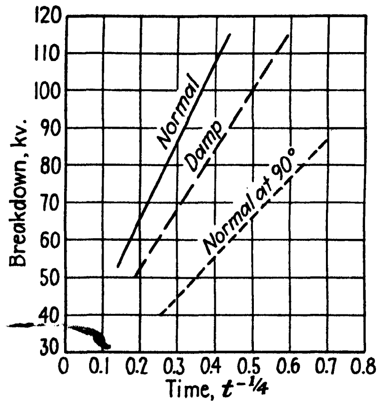


FIG. 15.—Volt-time curves for varnished paper board. (*S. Whitehead.*)

[1] *A.I.E.E.*, vol. 35, p. 783, 1916.

does not hold. At short times (upper part of curve) the agreement is better. With some materials the values can be included in a range between two lines established in agreement with the law. Curve *A* (Fig. 14) when plotted as a line satisfying Peek's equation, becomes Fig. 16. Time breakdown values are of great practical importance, since dielectrics are often subjected to potential for long periods. Short-time tests are useful chiefly for comparative purposes or to check uniformity. Design information is usually collected on the basis of accepted time tests in minutes or hours. After the first 5 or perhaps 10 min., the decrease in breakdown for most dielectrics is slight, so that

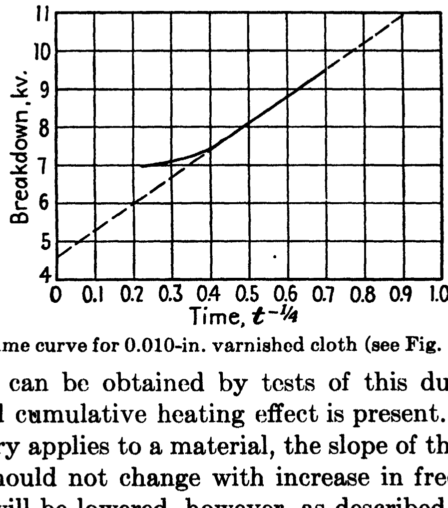


FIG. 16.—Volt-time curve for 0.010-in. varnished cloth (see Fig. 14). (*Rylander*.)

reliable data can be obtained by tests of this duration, unless some unusual cumulative heating effect is present. If Wagner's thermal theory applies to a material, the slope of the curve or the constant a should not change with increase in frequency. The value of V_0 will be lowered, however, as described later.

Temperature.—In general terms, we may say that with an increase in temperature, whether from internal or external causes, the breakdown voltage of dielectrics decreases, the dielectric loss increases, and the resistance decreases. The rate of change and the shape of the curves at different temperature ranges permit no inclusive statement. Apparently there are so many changes occurring in the dielectric, as the temperature is changed, that prediction of their total effect is impossible. Discontinuities in the temperature-breakdown relation may exist in some materials. In the discussion on causes of dielectric breakdown, the data of Moon and Norcross[1] showed three

[1] *A.I.E.E.*, vol. 49, p. 755, 1930.

regions of breakdown corresponding to three ranges of temperature within each of which a consistent slope exists, but with abrupt changes at the boundary temperatures (see Figs. 12, 13, Chap. II).

There is some satisfaction, in the face of all the confusing and conflicting data on the effect of temperature, in noting that most of the theories of dielectric breakdown would demand an unfavorable effect of increase of temperature. As might be expected, thick specimens are more seriously affected by temperature increases than thin specimens (Fig. 17). This would be especially true in materials having high dielectric losses. Transformer insulation (paper and oil) follows this trend; *i.e.*, it shows an

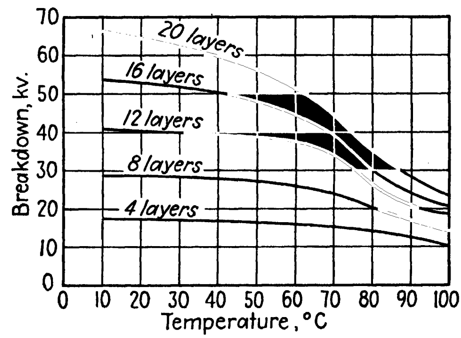


FIG. 17.—Effect of temperature on breakdown of 0.005-in. cotton-base paper in oil. (*S. Whitehead.*)

increased adverse effect of temperature for thick layers. In contrast, the effect of temperature changes on breakdown is slight for hard rubber and mica, which have high dielectric strength and very low losses.

The time of voltage application has a direct bearing on the effect of temperature changes. Short-time tests and impulse tests indicate little effect of temperature, but extended duration of voltage stress amplifies the deterioration with temperature increase. Many materials (resin plastics, for example) behave critically, in that limited ranges of temperature change affect breakdown; both above and below this band, however, the effect is much less. Thinner samples and shorter stress duration usually cause a narrowing of this critical temperature band.

At this point, something should be said about another complication—moisture. If moisture is present, speculation on the

effect of temperature is useless. Data can be found to prove almost any relation. In the apparently conflicting evidence, however, some consistency can be found. Materials, usually fibrous, that are moisture absorbing may improve in breakdown if subjected to increases in temperature, particularly in dry air to which the contained moisture can be given up. If these fibrous materials are first dried, they behave like others, showing a lowering of strength with higher temperatures. Examples of such materials are fiber, untreated cloth or paper, pressboard. Nonabsorbent materials, such as phenolic resin plate, varnished cloth, oiled paper, mica, and glass, conform to the expected rule of decreased strength with increased temperature under all conditions of humidity. Immersion in oil checks the release of moisture but also preserves the dryness of samples already dry. Consequently, no improvement with temperature would be expected in oil-immersed samples.

If the increase in temperature causes chemical changes, the dielectric strength may be affected irrespective of the usual temperature effect. Release of volatile vapors may improve or impair the remaining material, depending on their nature. Plastics when molded are usually not completely cured, and a further heating may cause an improvement by the release of conducting by-products of curing. A simple melting as in a gum or wax may have a good effect if any. On the other hand, glass is a fair conductor when melted.

Temperature increases affect the breakdown-thickness relation for most materials. Adding more material to obtain higher electric strength is less effective at high temperature, a fact that seems to be accounted for by the cumulative effects of dielectric losses in thick specimens.

Since the impulse strength is not much affected by temperature and long-time strength is, it follows that the impulse ratio $\left(\frac{\text{impulse-breakdown}}{\text{normal-frequency breakdown}}\right)$ rises with increase in temperatures. This does not mean that the impulse strength is higher, but only that the normal-frequency strength is lower. It is fortunate, however, that impulse strength is maintained, for then apparatus such as transformers are just as well protected against surges when hot as when cold.

TABLE I.—EFFECT OF TEMPERATURE ON THE DIELECTRIC STRENGTH OF INSULATING MATERIALS AND TEMPERATURE RISE DUE TO IMPRESSED VOLTAGE

[Test specimens were made by taping butt joints or wrapping the insulating tightly around 1 in. o.d., 1/16 in. wall brass tube 36 in. long (using no varnish or adhesive). A layer of tin foil 26 in. long was placed over the insulating layer, all being covered with a tight taping of treated tape. Thermocouples were placed inside the tube in contact with the brass wall 18 in. from the ends. The test specimens were placed in an oven at the temperature indicated. The brass tube was grounded during the test. Values given are averages of three tests for each point]

Material	1-in. tan tape	1-in. tan tape	1-in. black tape	1-in. black tape	Black treated cloth wrapper	Black treated cloth wrapper	Tan treated cloth wrapper	Tan treated cloth wrapper	Mica wrapper
Instantaneous Breakdown—Room Temperature									
Layer thickness	0.100	0.100	0.100	0.100	0.050	0.050	0.050	0.050	0.050
Total kv	48	48	54	54	44	44	41.25	41.2	22.5
Volts/mil	480	480	540	540	880	880	825	825	450
30 Min.—Step by Step (10%)									
Oven temperature	70	105	70	105	70	105	70	105	105
Applied kv. 1st step	12	12	13.5	13.5	11	11	10.3	10.3	9
Temp., °C., by thermocouple	71	186	72.5	170	76	143	75	124	158
Applied kv. 2d step	13.2		14.85		12.1		11.33		9.9
Temp., °C., by thermocouple	71		74		77		80		147
Applied kv. 3d step	14.4		16.2		13.2		12.36		10.8
Temp., °C., by thermocouple	73		76		77		89		167
Applied kv. 4th step	15.6		17.55		14.3		13.39		11.7
Temp., °C., by thermocouple	75.5		77		80		109		167
Applied kv. 5th step	16.8		18.9		15.4		14.42		12.6
Temp., °C., by thermocouple	77		78		89		128		161
Applied kv. 6th step	18		20.25		16.5				13.5
Temp., °C., by thermocouple	78		82		98.5				142
Applied kv. 7th step			21.6						14.4
Temp., °C., by thermocouple			90						198
Applied kv. 8th step			22.95						15.3
Temp., °C., by thermocouple			95						271
Applied kv. 9th step									16.2
Temp., °C., by thermocouple									314
Total time, min., at failure	163	21	235	16	176	6	129	5	256

The preceding data (Table I) taken on 0.010-in. treated cloth tape wrapped on a metal tube to a thickness of 0.10 in., illustrate two points with reference to the effects of temperature. (1) The long-time breakdown strength was seriously impaired at high temperatures. When 10 per cent of the room-temperature breakdown was initially applied and increased 10 per cent each half hour until breakdown occurred, the final values were only 40 to 50 per cent of the cold breakdown. (2) The losses due to applied voltage increased the temperature of the dielectric appreciably above the ambient. From these facts, it is evident that heating from both internal and ambient sources must be taken into account in predicting the margin of safety.

Frequency.—Experimental data on the effect of increases in frequency on breakdown voltage of dielectrics is difficult to correlate. Frequency effects seem to be tied in with temperature, time, and other factors, so that a given statement holding for one set of conditions is apparently contradicted by data for other combinations.

Qualitatively it is logical to reason that *losses per cycle* in a dielectric may be constant if other conditions are constant. The losses would then increase proportionately with frequency. It follows that the temperature of the dielectric will then be higher for higher frequencies, and we already know that dielectric strength decreases with increase in temperature. Such a conclusion depends for its validity on the assumption that loss *per cycle* is independent of frequency. In our discussion of dielectric loss, it was noted that some experimental facts are at variance with this and that Wagner attempted to reconcile the observations of decreasing, constant, and increasing losses per cycle by the concept of an absorption constant having a "humped" curve shape with increasing frequency. Whether we accept Wagner's explanation or not, the fact remains that not all materials exhibit a constant loss per cycle with increasing frequency. The final result, however, is usually a lowering of breakdown voltage with increase in frequency, but not a uniform rate over the range and not the same for different dielectrics (Fig. 18). If the resistivity is low, frequency has less effect. By way of illustration, we observe that, at high temperatures, glass breakdown is little affected by frequency changes. Moist insulation (fiber, pressboard) behaves similarly.

For many organic materials such as paper and cloth a fairly satisfactory relation is

$$V = \frac{V_0}{f^n}$$

where V = breakdown voltage at any frequency.

V_0 = breakdown at a reference frequency (*e.g.*, 60 cycles).

f = frequency.

n may be in the range 0 to 0.5.[1]

At least we know that breakdown strength at higher than normal frequency is impaired enough to require care in testing of transformers and condenser bushings. Transformers and

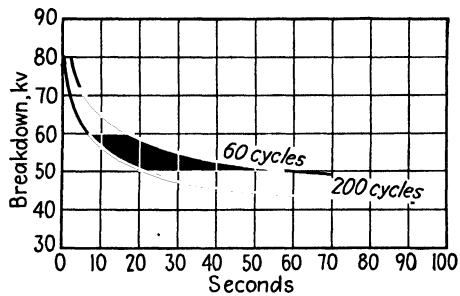


FIG. 18.- Effects of frequency and time. Pressboard in oil at 25°C. (S. *Whitehead.*)

coils are often given an overpotential test between turns by applying higher than normal frequency. It is always necessary to limit the duration of such tests to avoid heating of the insulation and the possibility of failure by breakdown. In the testing of porcelain insulators by high frequency to locate defects the test must be short or the porcelain will be heated and fail without having any defects of structure. Peek[2] found for transformer insulation that in 1-min. tests, starting at 25 cycles, the breakdown voltage for 60 cycles was 10 per cent lower, for 120 cycles 20 per cent lower, and for 500 cycles 25 per cent lower.

Wave Form.—Commercial variations or deviations from a pure sine wave have no appreciable effect on breakdown of solid insu-

[1] VOGEL, F. J., *A.I.E.E. Trans.*, vol. 43, p. 340, 1924.

[2] PEEK, F. W., "Dielectric Phenomena in High-voltage Engineering," McGraw-Hill Book Company, Inc., New York, 1929.

lation tested with such sources. Very little accurate work has been done, but the experiences in cable testing and other fields bear out this statement.

Extremes of alternating-current distortion may be important, particularly with gases and with solids that fail thermally. Gaseous breakdown is chiefly determined by the maximum voltage, or crest value of an alternating-current wave. Early high-voltage testing transformers had notably poor wave shape, which stimulated the development of crest-reading devices such as the crest voltmeter.[1] The sphere gap, early developed as a voltage-measuring standard, is a crest-measuring device even though it is usually calibrated in equivalent r.m.s. sine wave terms. The improvement in design of testing transformers and associated generators has corrected the wave-shape difficulty and reduced the importance of crest-voltage determinations.

Many solids exhibit a thermal type of breakdown under usual conditions. For such cases a peaked wave with a given maximum might not cause breakdown, whereas a flat-topped wave with the same maximum might produce enough more heat to produce failure. The effective root mean square value controls the internal losses and resultant heating.

Conditions change, as we have so often noted, in the same dielectric. Certain materials (*e.g.*, glass) have a thermal-instability type of breakdown at high temperatures and at low temperatures a disruptive breakdown. The first is a function of r.m.s. value, and the second is a crest- or maximum-voltage effect.

This brings us to a consideration of disruptive breakdowns occurring with impulse voltages, which might be included as special cases of wave-shape phenomena.

The impulse breakdown of most insulation, gases, liquids, and solids, is substantially higher than the normal-frequency alternating-current breakdown. The relation between these two values is termed the "impulse ratio," which for solid transformer insulation may be 2.2 to 3.0.[2] Whether impulse breakdown is higher than direct-current breakdown seems indeterminate in

[1] CHUBB, L. W., *A.I.E.E. Proc.*, vol. 35, p. 109, 1916.
MINER, D. F., *Elec. Jour.*, vol. 22, p. 571, 1925.

[2] MONTSINGER, V. M., *Gen. Elec. Rev.*, 1937, p. 454.
VOGEL, F. J., *Elec. Jour.*, p. 306, 1937.

general terms. Peek[1] reports a comparison of various voltage forms on the breakdown of two layers of varnished cloth, of a total thickness of 0.60 mm.

TABLE II

Source	Crest Kv. per Mm.
Single impulse (equivalent to 200,000 cycles or 2.5 microsec. to crest)	108
D. c.	85
60 cycles (short time)	53
60 cycles (1 min.)	46
90,000 cycles (1 min.)	17.6

For thicker specimens the direct-current and impulse curves cross (kilovolts vs. thickness), so that the direct-current breakdown becomes higher than impulse, possibly because of the poorer distribution of gradient in thick samples under impulse test.

Some tests on about the same thickness of mica by A. E. G. (Germany), described by S. Whitehead,[2] show the direct-current tests highest by a wide margin. The impulse tests applied, however, were of long duration (285 microsec.), which may account for the low impulse values, which were in fact lower than the normal-frequency tests. It is confusing to compare impulse tests unless there is some basis for standardization. After many years of investigation and comparison there have been established two standard impulse-wave shapes, the 1 × 5 and the 1½ × 40. The first figure of each combination defines the time in microseconds from the initiation of the impulse to the crest of the wave. The second figure is the time from start to a point on the tail of the wave when the voltage is reduced to one-half the crest. This shape of wave was chosen to be substantially in accordance with natural lightning behavior and is a form obtainable in practical testing equipment. The faster wave (1 × 5) is not used so extensively as the 1½ × 40 wave (1½ microsec. to the crest and 40 microsec. to half the crest voltage).

[1] *Op. cit.*, pp. 381, 394.

[2] WHITEHEAD, S., "Dielectric Phenomena," vol. III, p. 163, D. Van Nostrand Company, Inc., New York, 1932.

At this point, we should introduce the concept of *time lag*, a useful term that is important in reference to coordinating the insulation of high-voltage equipment. For impulse waves, there is a time-voltage relationship which resembles that for normal frequency, described previously. For any impulse of standard shape ($1\frac{1}{2} \times 40$) the time required for breakdown of any type of insulation (gas, liquid, solid, or combinations) depends on the crest voltage reached. As an example, a specimen subjected to a $1\frac{1}{2} \times 40$ wave with 100-kv. crest might break down 30 microsec. after start of the wave, which would be well out on the tail of the wave. If the wave had reached a crest of 150 kv., the time of breakdown might have been 3 microsec., which would be shortly after the crest was past. And so a curve can be constructed of breakdown time in microseconds vs. crest voltage of the standard wave shape. Such a curve is called a time-lag curve. By its use, various insulations can be compared to determine which might fail first under a given condition where several kinds might be simultaneously exposed. The steepness of the respective time-lag curves is different. For example, air gaps have a steep curve; *i.e.*, there is a large difference between the voltage necessary to cause breakdown in a few microseconds and that required to produce flashover in many microseconds. Transformer insulation, on the other hand, is less sensitive in time of breakdown. The voltage for 50 microsec. breakdown is not much lower than the voltage for 2 microsec. breakdown.

Repeated Stress.—By comparison with mechanical relations, it would be expected that repeated electrical stresses might cause permanent and increasing damage to insulation. Experience bears this out, provided that the stress is high enough.

From such conflicting data as we have available, it seems safe to say that if voltage above the long-time breakdown voltage (V_0 of Peek's law) is applied, even for short intervals, some damage is done; and of course the severity is related to the amount above the ultimate failure voltage. There seems to be support for the theory of a constant volt-time life of insulation. At a given overpotential (above V_0), there may be a total time during which a sample will resist failure, and it makes little difference whether the time is continuous or a summation of several applications. This seems more nearly true if the stress-application periods are relatively short, although very short

alternating-current stresses seem to have little deteriorating effect. A few materials benefit from a rest period for "recovery" (see Fig. 19)[1] if the rest period is long enough, particularly if they are subject to rapid heating by dielectric losses.

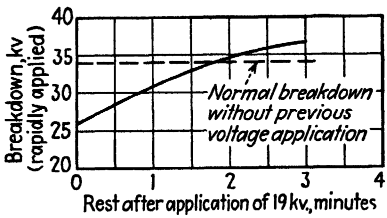


FIG. 19.—Effect of rest period on breakdown of treated paper. (*S. Whitehead.*)

Under impulse test with standard wave ($1\frac{1}{2} \times 40$), a repetition of impulses below the single-impulse failure voltage may cause ultimate failure. The danger level seems to be[2] 80 per cent of the single-impulse failure voltage.

The Rate of Voltage Rise.—The rate of voltage rise in testing of insulation is important because of the time-voltage relation that has already been discussed. For short periods on alter-

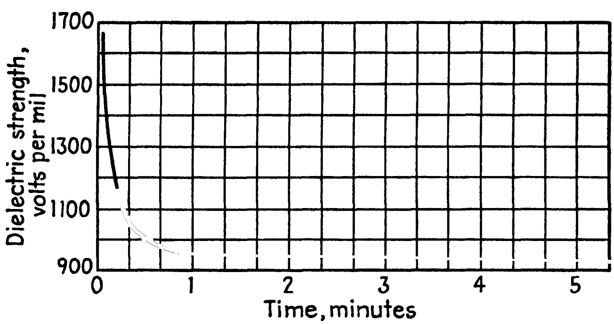


FIG. 20.—Effect of rate of increase of voltage on dielectric strength of black varnished cambric. (Tests made with 2-in. flat electrodes with $\frac{1}{4}$-in. radius edge.) (*A.S.T.M. Stds. D*-9, 1940, *p.* 17.)

nating current and for impulse waves, we have noted that higher breakdown strengths are usual than for long exposure. If, then, the test voltage is raised very rapidly, a falsely high value of breakdown may occur, when compared with other tests made at lower rates. The American Society for Testing Materials[3] illustrates the effect of rate of voltage rise by the curve Fig. 20.

[1] CLARK, F. M., *A.I.E.E.*, vol. 44, p. 158, 1925.

[2] PEEK, *op. cit.*, p. 243.

[3] A.S.T.M. Standards on Electrical Insulating Materials, November, 1940, p. 17.

Cloth tape was tested in a standard manner, except that the voltage was increased continuously at rates which caused failure in times covering the range up to 6 min. Nearly 50 per cent increase in breakdown was obtained when breakdown occurred in 0.2 min., compared with 2 min.

A degree of standardization has been accomplished by the A.S.T.M. in setting up standards of rate of rise for various classes of materials. These should be consulted in selecting test equipment and in making tests for comparative purposes.

Thickness.—Thickness has already entered the picture in connection with volt-time curves and theories of breakdown. Materials may be roughly divided into two classes: (1) those which show a proportionality (at least in some regions) between breakdown voltage and thickness, and (2) those which show a decreasing unit strength with increasing thickness.

Glass and mica are two prominent examples of the proportional class, particularly for thin sections. In many materials the relation of thickness to voltage of breakdown is not simply stated, but an expression that holds reasonably well is: $V = Ad^n$, where V is breakdown voltage, A is a constant, d is thickness, and n is always less than unity and is often approximately 0.5. The exploration of three regions of breakdown by Moon and Norcross[1] established for glass a value of $n = 1$ at 0°C., $n = \frac{2}{3}$ in the range 50 to 125°C., and $n = \frac{1}{4}$ to $\frac{1}{2}$ in the range 250 to 300°C.

Air breakdown in a sphere gap follows an exponential curve of voltage spacing but in a needle gap has a substantially proportional relation except at low voltages (30 kv. or less). Above this point (1.61 in. spacing), needle gaps can be roughly figured at 10 kv. r.m.s. per in. separation.

Breakdown of oil at large spacings between spherical electrodes follows an exponential law, influenced by the radius of curvature.

The general form of equation for 3-min. hold tests is[2]

$$kv = A \log \frac{S}{a}$$

where A and a = constants.
S = spacing, in.

[1] *Op. cit.*

[2] Miner, D. F., *A.I.E.E.*, vol. 46, p. 248, 1927.

An approximate general equation, taking into account the size of the electrode, is

$$kv = 177\sqrt{d}\log\left(1 + \frac{S}{0.16}\sqrt{d}\right)$$

where d = diameter of electrode, in.
S = spacing, in.
For 2 in. diameter

$$kv = 250\log\left(1 + \frac{S}{0.266}\right).$$

For ¼ in. diameter

$$kv = 88.5\log\left(1 + \frac{S}{0.08}\right).$$

Moisture.—Some of the effects of moisture have already been mentioned under Temperature. Some absorbent dielectrics are

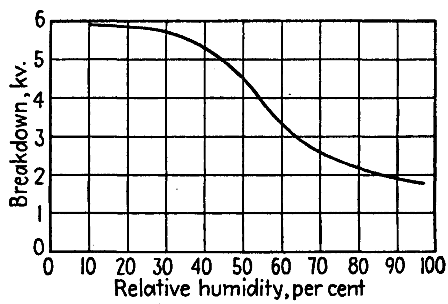


FIG. 21.—Effect of humidity on breakdown of paper (1 cm. dia. spheres). (*S. Whitehead.*)

known to improve in breakdown if the moisture is driven off. On the other hand, impervious dielectrics as mica, glass, or even well-varnished or impregnated fibrous materials show little effect with humidity unless under long exposure to extreme conditions. Moisture sometimes (as in fiber) evens out the voltage gradient so that higher test values are noted.

With absorbent insulation, the curve of breakdown vs. humidity has the same form as the breakdown-temperature curves, with slow changes at the beginning and end (Fig. 21). Moisture may have two effects: (1) It may cause increased conduction or electrolytic losses and induce heating. (2) Or it may

form discontinuous globules or elongated drops which increase the local internal flux concentrations.

Mechanical Stresses.—We have remarked that mechanical stress which partly disrupts the structure of solid insulation may decrease the breakdown strength, particularly for crystalline materials. In such materials, incipient cracks precede electrical breakdown. A practical use is made of this effect in designing a test to ensure the performance of porcelain suspension insulators. The test is known as the combined mechanical and electrical test (or, abbreviated, the M. & E. test). The insulator is placed in a tensile machine properly insulated so that a voltage 75 per cent of flashover (and approximately one-half the puncture voltage) can be continuously applied. Then the tensile load is increased until electrical failure takes place. An insulator whose ultimate breaking strength may be 20,000 lb. may fail electrically at two-thirds this value, showing that some disruption of the porcelain must be present, long before ultimate breaking. The electrical test is a sensitive indicator of mechanical damage.

Effect of Electrodes and Ambient Medium Used in Testing.—In the testing of dielectrics, to obtain the characteristic properties discussed in previous chapters, we have seen that the electrical conditions of test (rate of voltage rise, frequency) have an important influence. We have also observed that the condition of the sample (temperature, thickness, moisture content) also has a great effect on breakdown. We shall now discuss another group of factors: the choice of physical surroundings, involving the electrode size and shape and, in the case of solids, the medium in which the sample is immersed. After determining, for instance, what effect the electrode design has under a variety of conditions, we can better decide what sort of standard test apparatus gives most reliable results.

The objective of an insulation test may be to determine: (1) the average properties; (2) the maximum values (such as theoretically maximum breakdown of air in a uniform field); or (3) minimum properties under worst service conditions. The choice depends on the intended use of the test data.

1. Sometimes we need merely a comparison, either with previous specimens of the same kind or with similar samples of another material. Under such circumstances a fairly represen-

tative test which gives results easily duplicated will suffice. The standard oil-test cup is an example.

2. If the maximum possible breakdown were desired, another form of test would be selected, probably with more attention given to a favorable arrangement of the dielectric field. For example, a test that gives maximum breakdown conditions for air is the sphere gap.

3. Frequently, we like to know what properties are obtainable in usual machine construction, where sometimes unavoidably the insulation is used under most adverse dielectric field conditions. Test of tape wrapped on a copper bar might illustrate such an unfavorable condition; or the flashover of a porcelain insulator, whose sharp hardware distorts the field, may indicate the worst condition for a given air path.

The effect of the test electrodes will be examined for gases, liquids, and solids principally with relation to dielectric strength.

The following factors in physical arrangement of test will be discussed to complete the picture of the effect of variables on the behavior of dielectrics.

a. Configuration of electrodes and resulting dielectric fields.

b. Area of electrodes.

c. Material of electrodes.

d. Nature of ambient medium (for solid dielectrics).

a. ELECTRODE CONFIGURATION. 1. *Needle Points.*—Stress concentration is present with pointed electrodes. At high potentials the gradient may be high enough to produce local breakdown of the surrounding dielectric, particularly gas or liquid. Localized breakdown persisting for even a short time may lead to total failure, particularly with solids. Corona up to a certain limit can exist in gases indefinitely without proceeding to breakdown, but the breakdown value will be influenced by the degree of ionization present. It would therefore be expected that the breakdown between needle points with a gas, liquid, or solid dielectric would give minimum values. With gases and liquids, this is the case; but with some solids exceptions are observed, especially with heterogeneous dielectrics. Where failure is determined by weak spots, the breakdown for needle points may be higher than for larger electrodes, since there will be less area under test and less chance of inclusion of weak filaments. Samples of varnished cloth frequently show this effect. On the other

hand, homogeneous materials like hard rubber do not show this effect.

Needle-point tests are, however, very useful in testing for air breakdown or flashover to find the worst possible condition that might be expected in structures with sharp edges or points.

2. *Disks.*—This common form of test electrode is used sometimes with sharp edges and sometimes with rounded edges. To limit definitely the included area and volume, the sharp- or square-edged electrode is required for resistivity and loss tests.

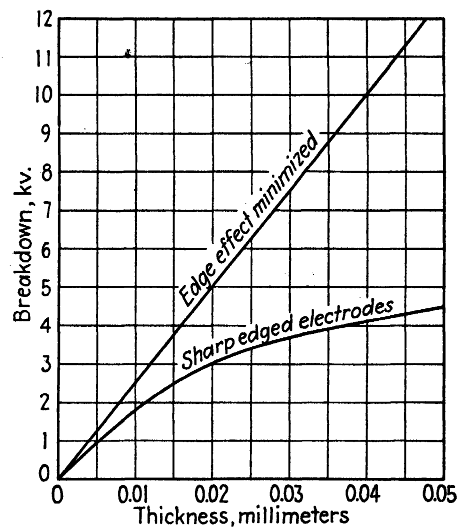


FIG. 22.—Edge effect in breakdown of mica. (*S. Whitehead.*)

Where applied stress is high, loss-measuring tests require a guard ring to assure uniform field. For breakdown tests, it would seem that the stress concentration would depend on sharpness of the edge and that breakdown would increase as some function of the curvature of the edge. "Edge effect" is a term used to describe the usual lowering effect of stress concentration on breakdown. Much work has been done to eliminate or reduce edge effect in test procedures. It is not always true that sharp-edged electrodes give low breakdown. Whitehead[1] reports that edge sharpness has little or no effect in tests on sheet organic insulation. Clark and Montsinger noted the same for thin specimens. The location of failure was observed to be near the edge; but the

[1] *Op. cit.*, p. 76.

value on the average was no less than when breakdown occurred at the center, where supposedly the field is uniform. On the other hand, Whitehead presents a curve on mica (Fig. 22), showing a great difference if edge effects are reduced. He also gives a curve by Tressler (Fig. 23) showing relation of radius of edge to breakdown, which confirms by far the more common experience.

The author has found that curvature of electrodes with the standard A.S.T.M. method of testing varnished cloth produced considerable difference. The standard 2 in.-diameter disk with ¼-in. radius of edge gave a 1-min. breakdown on a certain

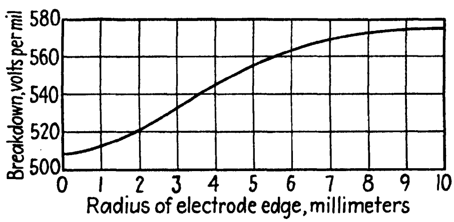


FIG. 23.—Effect of electrode edge on breakdown of treated-sheet insulation. (*S. Whitehead.*)

sample of 12.5 kv. When 2-in. disks with a square edge were used, the breakdown occurred at 8.7 kv., a reduction not accounted for by the increase in contact area.

L. A. Philpott[1] compared breakdown of 0.010-in. varnished cloth in oil, using a variety of disk, washer, and torus electrodes. His data show a definite effect of curvature of edges. A few typical data from his work are given below.

TABLE III

Electrodes	Kv. for 20-sec. breakdown	Kv. for 170-sec. breakdown	Percentage breakdown at edge
3-in. square-edge disk ⅛ in. thick	14.0	11.6	50
3-in. round-edge disk ⅛ in. thick	14.6	12.4	20
3-in. torus, 2½-in. hole	17.5	13.8	
2-in. square-edge washer, 1½-in. hole	17.1	13.2	70
2-in. torus, 1½-in. hole	18.0	14.1	20

[1] Thesis, University of Maine, 1938.

It will be noted also that area has an effect, higher breakdown occurring with smaller area. This is discussed under Area of Electrodes, page 61. Philpott also reported the location of breakdown near the edge of sharp electrodes.

From the available data, which is not consistent, it is difficult to make a positive statement; but it seems safe to say that the edge effect, as determined by changes in electrode-edge radius, is less prominent in long-time tests or in high-temperature tests or for very thin samples (10^{-2} to 10^{-4} cm.). The edge curvature has a marked effect with usual insulation samples tested by accepted standard methods. For this reason, specifications for test procedure usually fix the edge radius. In oil tests a square-edged disk is used at a short spacing. This is justified, for the total voltage of breakdown is usually insufficient to produce ionization at the edge.

3. *Concentric Cylinders.*—The electrostatic field between two concentric cylinders has the virtue of being uniform except at the ends of the cylinders. In practice the ends are frequently flared to relieve stress or protected with dielectrics of high strength (barriers and compounds) to prevent failure in this region. The cylindrical configuration finds its practical counterpart in several apparatus parts such as single conductor cables, bushings, and insulated conductors. This form of electrode is often used in testing tape or insulating-wrappers such as are used in turbo-generator windings. The insulation is applied in the desired number of layers on a metal tube or rod and finished with a metal-foil layer as the outer electrode. Sufficient insulation surface is left at the ends of the metal foil to prevent flashover. The breakdown between cylinders cannot be closely correlated with breakdown between disks for most solid insulation. Laminated Bakelite tubing, for example, may test 10 to 30 per cent higher than the same material in sheet form. Cylindrical specimens are frequently used in making loss measurements, so that the mechanical structure, density, etc., may approach service conditions.

A feature of cylindrical electrodes is the critical ratio of inner- and outer-cylinder diameters for breakdown. There is an optimum ratio for minimum gradient that can be calculated from the usual formula.

$$E_N = \frac{V}{(r \log b/a)}$$

where E_N = radial stress at radius r.
V = total applied voltage.
b = outer-conductor radius.
a = inner-conductor radius.

Minimum gradient exists when $b/a = 2.72$ (base of Napierian logarithms).

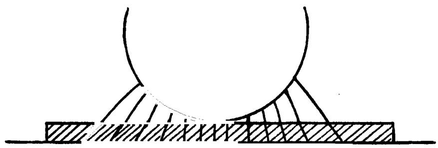


FIG. 24.—Two dielectrics in series with sphere and plane electrodes.

This is of importance in the design of cables.

4. *Spheres.*—Spheres are commonly used in three ways: two spheres in line, sphere and plane, and two concentric spheres. The field in each case is simple, uniform (at surface of sphere),

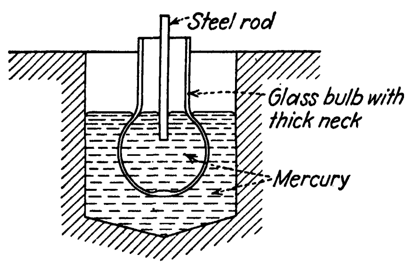


FIG. 25.—Method of testing glass to eliminate edge effect. (*Moon and Norcross.*)

and easily calculable. Spheres in air, opposite each other, are used as standards for the measurement of voltage. This form is used chiefly for breakdown tests on liquids or gases. In the case of flat solids, it is evident (Fig. 24) that the lines of force pass through the sample and the surrounding medium in series. This causes unequal gradient distribution and local breakdown. Tests with sphere and plane or sphere and sphere for flat solid insulation are usually quite erratic. The perfectly uniform field between two concentric spheres lends itself to tests on materials that can be molded in this shape. Blown-glass spheres coated inside and outside with a conductor (silver or mercury) is an excellent form of test (Fig. 25). Extremely high unit values of breakdown of glass have been obtained in this way. Fusible

compounds poured between metal spheres can also be tested. It is difficult, however, to remove all bubbles or inclusions, and erratic results are frequent.

To overcome the series dielectric arrangement between sphere and plane in the testing of sheet materials, recesses are sometimes made to fit the sphere. Embedded electrodes improve the field and the contact with the sample. It has been noticed that, especially with shallow depressions and large-radius spheres, the

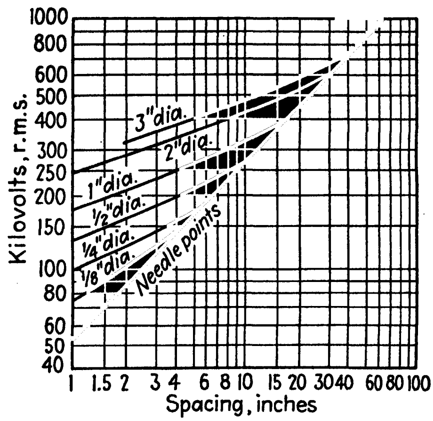


FIG. 26.—Breakdown of oil with spherical electrodes, three-minute-hold tests.

breakdown frequently occurs away from the center (thinnest section of insulation), a tendency that is stronger for better materials. The actual values are not necessarily low for breakdown away from the center, but variation between tests is wide. The intimacy of contact plays a great part, also. In most cases, therefore, because of variable results and the difficulty of arranging a suitable recess with a good "fit," this electrode arrangement is not widely used. It has been observed that tests are somewhat better between two embedded spheres than between one embedded sphere and a plane.

The radius of curvature of spherical electrodes has an important bearing on breakdown of liquid dielectrics, such as oil. Corona will form in oil if the potential gradient is sufficiently high. The author's work on oil breakdown[1] at large spacings illustrates the effect of surface gradients. Cylinders with spherical ends were used to avoid the field-distorting effects of the usual small shanks.

[1] *A.I.E.E.*, vol. 46, p. 248, 1927.

Spacings up to 60 in. were explored with spherical electrodes of various diameters, from 0 to 3 in. Figure 26 summarizes the results. It appears that all curves join the needle-point curve at their respective critical spacings, which means that large curvature is ineffective at large spacings. At short spacings (1 in.), the voltage that can be held for 3 min. with 3-in. diameter electrodes before breakdown is about five times the voltage possible with needle points. At 40-in. spacing, the two curves join.

An explanation of these test results may be offered as follows. It is assumed that there is a definite potential gradient necessary for breakdown in oil. When this gradient is reached at the surface of the electrode, the oil surrounding the spherical surface is ionized, the effect being to increase the effective diameter. Whether a complete breakdown follows will depend on whether this increased effective diameter reduces the gradient sufficiently. With large spacing of electrodes, ionization at the electrode surface decreases the gradient and the accompanying corona may not lead to breakdown. With small spacings, on the other hand, a complete breakdown will follow the surface ionization. It thus appears that for a given size of electrode there is a critical spacing, below which breakdown follows surface ionization and above which corona will exist before breakdown. This behavior is similar to that of air. The point where the breakdown curve of an electrode of any size joins the needle-gap curve may be interpreted as the point at which corona or ionization appears. Observation of corona in oil approximately confirms this statement.

b. Area of Electrodes.—With gaseous and clean liquid dielectrics, the effect of area of electrodes on breakdown is slight; with solids, the effect of area is pronounced.

Examining the problem of breakdown from one viewpoint, it might appear that large-area electrodes will conduct heat (from losses) better and that higher values of breakdown should be obtained. It would be expected, however, that large electrodes would cover more weak filaments than small electrodes and that the chance of breakdown would be greater. With these two opposing factors, the weak-spot effect is usually dominant. Experimental results generally indicate a marked decrease of dielectric-strength values as the area of testing electrodes is increased.

A distinction should be noted between heterogeneity and weak spots. The former applies to a composite material that contains particles more or less uniformly distributed, having different dielectric properties. The dielectric constants of the components may differ and cause poor distribution of stress and a lower breakdown than might be expected from characteristics of the components. But the breakdown may occur at any one of several

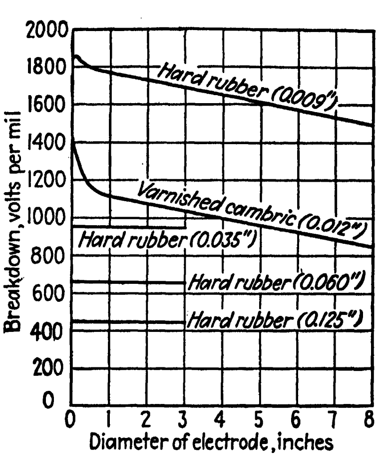


FIG. 27.

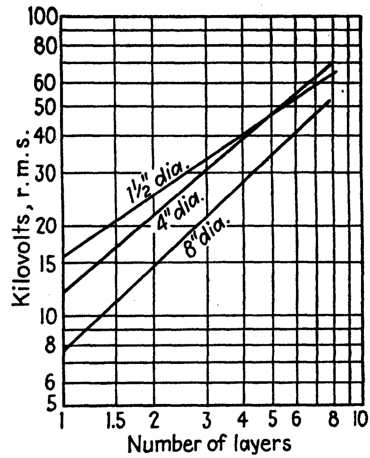


FIG. 28.

FIG. 27.—Effect of electrode area on dielectric strength tests in transformer oil (0.012-in. varnished cambric and 0.125-in. hard rubber from A.S.T.M. 0.009-, 0.035-, and 0.060-in. hard rubber from Farmer).

FIG. 28.—Effect of electrode area, varnished cloth in oil. (*Montsinger*).

like points. In the case of weak spots a deterioration of material is assumed or a filament of moist or low-resistance foreign substance. In such a condition, breakdown will occur at the definitely weak spots. We may, however, admit that heterogeneous materials are more likely to have weak spots because of their structure.

Before making any general statements, let us review some of the experimental data of various investigators.

The A.S.T.M.[1] gives curves (Fig. 27) showing the relation between diameter of disk electrodes and dielectric strength for thin varnished cambric and thick hard rubber. With the thin and nonhomogeneous varnished cloth, an increase of ¼ to 4 in. diameter reduces the apparent dielectric strength over 30 per

[1] A.S.T.M. Standards on Electrical Insulating Materials, January, 1939.

cent. No change is observed with the thick, homogeneous hard rubber.

Farmer's tests on hard rubber[1] in oil show (Fig. 27) further that thin sheets (9 mils) of this material also respond appreciably to changes in disk-electrode diameter, whereas thick sheets (35 mils up) show no effect.

V. M. Montsinger[2] (Fig. 28) found that the dielectric strength of varnished cambric was affected by the electrode diameter, but his results differ from Farmer's.

Many more tests could be presented, but they all show similar effects, giving pretty general agreement. We may well ask whether this change is all due to area of the electrodes. An analysis based on probability of weak spots related to electrode area was worked out by Whitehead.[3] The calculated curves agree with some experimental results, but the solution is not wholly satisfactory.

F. W. Peek stated that the strength-area curve follows a probability law except for small areas. There is a strong suspicion that the whole story is not covered by weak-spot probability. The strongest evidence against probability is the work of Kennelly and Wiseman.[4] In their tests, instead of increasing the diameter of electrodes, they increased the number of similar small electrodes connected in parallel. Their first results confirmed the usual results. Kennelly and Wiseman then inserted high resistance in series with each of the unit electrodes and found no change in dielectric breakdown as the number of electrodes increased. Hill[5] repeated the experiment and partly confirmed the work of Kennelly and Wiseman. Hill ascribes the lowering effect of single large-area electrodes to high-frequency areas which may arise from poor contact. He has produced similar effects by superimposed transients. As an extreme case, glass 0.25 in. thick was punctured at 1,200 volts by concentrating a 6-million-cycle arc discharge at a point on the surface. High-frequency discharges presumably exist at the edge of electrodes also, and in the case of several small electrodes this might be expected to

[1] *A.I.E.E.*, vol. 32, p. 2097, 1913.
[2] *A.I.E.E.*, vol. 43, p. 337, 1924.
[3] *Op. cit.*, p. 92.
[4] *Elec. World*, vol. 77, p. 1130, 1917.
[5] *Elec. Jour.*, vol. 31, p. 324, 1934.

be considerable; but apparently the arc discharges due to poor contact in large electrodes is the dominant factor.

An interesting demonstration of the effect of transients or high-frequency arcs on losses was made by Hill.[1] He wound three similar elliptical-section brass tubes with insulation and applied metal foil on the outside. Voltage high enough to produce a discharge at the edge of the foil was applied to one sample, and the temperature rise due to losses noted. Then the other two tubes were connected in parallel with the first and spaced sufficiently so that no effect of one on the others would occur. With three samples, the energy of the high-frequency discharge would be increased in each. The temperature rise of the first sample increased 20 per cent. Removal of the two added samples caused the temperature of sample 1 to return to the original value. It seems clear, therefore, that, with materials having a thermal breakdown, high-frequency effects greatly influence the breakdown.

From the foregoing evidence, we can conclude that large electrodes give an appreciably lower breakdown than small electrodes, particularly with thin samples of material, susceptible to thermal deterioration. The lowered breakdown is partly explained by the probability of weak spots, but this must be supplemented by further conceptions, probably related to effects of high frequencies resulting from poor contact over the electrode area.

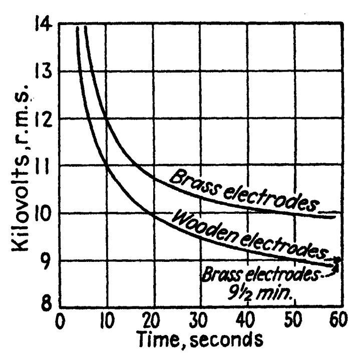


FIG. 29.—Effect of electrode material on breakdown of varnished cloth. (*Rayner.*)

c. MATERIAL OF ELECTRODES.—No substantial difference occurs in breakdown tests using electrodes of different metals. Copper, brass, and aluminum are preferred because of ease of manufacture and their noncorrosive properties. On the other hand, the condition of the metal surface influences the test. For sphere gaps in air, the surface must be carefully polished and cleaned. Small particles of dirt or rough metal points will initiate breakdown at low values with gases, liquids, or solids.

[1] *Op. cit.*

When electrodes of widely different thermal conductivity are compared, we observe different behavior. In work done on fiber, celluloid, and similar materials for the Electrical Research Association, Whitehead found little difference between brass and wooden electrodes. On the other hand, we have curves submitted by Rayner[1] exhibiting a difference between wooden and brass electrodes; but it seems likely that the two curves will coincide at long times, perhaps 10 min. (Fig. 29). This indicates a possible effect of heat transfer or heat conduction that will be more effective with the metal electrodes for a short interval of time.

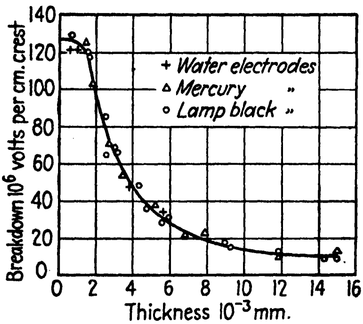


FIG. 30.—Electric strength of thin glass films. (*Sinjelnikov and Kurtchakov.*)

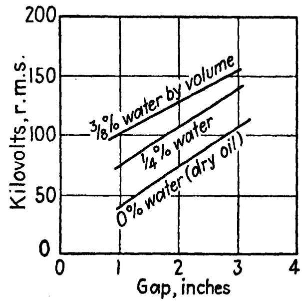


FIG. 31.—Dielectric strength of wet oil, spheres 3/8 in. in dia.

A comparison of breakdown of thin films of glass (1 to 15 $\times$ 10^{-5} cm.) using lamp black, mercury, and water as electrodes was made by Sinjelnikov and Kurtchakov[2] (Fig. 30). The points all lie on the same curve.

Differences, where found, may therefore be ascribed to thermal effects in the insulation, and not to any physical or chemical property of the electrode material.

d. AMBIENT MEDIUM.—It is common practice to test samples of solid insulation in air whenever possible; but when the sample is thick or of such shape that failure over the surface (flashover) takes place before the breakdown or puncture voltage is reached, immersion of the sample in transformer oil is substituted. The surface-flashover path then has a breakdown point high enough to permit test of the material. Where a choice of either air or oil can be made and the test results compared, it is often found that

[1] *J.I.E.E.*, vol. 49, p. 3, 1912.

[2] *Comptes Rend. Acad. Sci.*, U.R.S.S., 1926.

there is not an agreement. A disconcerting phenomenon that an experimenter encounters is finding that a sample tested in poor oil (wet or slightly conducting) behaves better than in pure new oil. The author had this experience about 1926 in puncture testing of porcelain suspension insulators. A group of insulators was tested one day in an infrequently used tank of oil which was later found to contain considerable moisture. The puncture values were about 20 per cent higher than usual. It was then

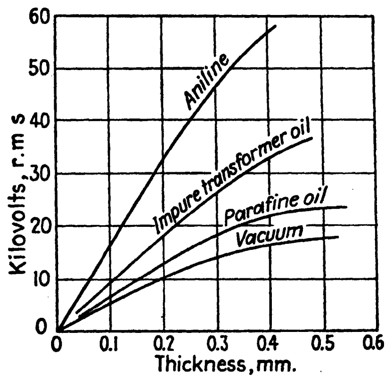


Fig. 32.—Effect of ambient medium on breakdown of glass.

found that deliberately putting water into good oil would improve the puncture values of samples tested in such oil. Small sphere gaps placed in oil with 1-in. or greater spacing responded similarly, giving higher breakdown when finely divided waterdrops were forced into the gap (Fig. 31).

The experiments of several investigators have shown definitely that conductivity of the test medium will modify the breakdown of solid samples. Several media have been tried, such as aniline in oil, organic acids in oil, xylene, alcohols, tricresyl phosphate, glycerin, and many mixtures. These liquids are only slightly conducting, having resistivities in the range 10^4 to 10^9 ohm-cms.

The effect of the medium is not confined to specific dielectrics. In fact, most insulation behaves similarly.

Others have reported increases in mica breakdown as great as 4 to 1. Figure 32 shows tests on thin glass by Inge and Walther[1] giving a 3-to-1 ratio between tests in aniline and in vacuum. What, then, is the cause of this peculiar behavior? Apparently

[1] *Arch.-Elek.*, vol. 24, p. 209, 1930, 1936.

the key to the explanation is contained in the expression "edge effect." Hill[1] discusses this in detail and gives conclusive evidence that high-frequency discharges, whether at the electrode edge or at poor contact areas, have a serious influence on breakdown. By various means such as points and foil shields, he purposely introduced discharges and demonstrated their lowering effect. Discharges on a lead-in wire to a porcelain casing, being tested completely under oil, were shown to cause a boring into the porcelain for a distance of 12 in. (total length 60 in.). This partial breakdown, sometimes causing pieces of porcelain to break off, was eliminated by shielding the lead wire.

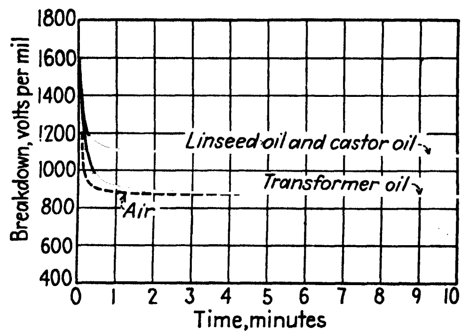


FIG. 33.—Effect of ambient medium on breakdown of varnished silk. (*S. Whitehead.*)

It seems probable that a test more nearly indicative of the properties of the material is possible when "edge effect" is eliminated. It has been the observation of the author and others that breakdown occurs more often in the uniform field or in the center of electrodes when edge effect is minimized. The frequency of breakdown near electrode edges when discharges are present makes one suspicious of the validity of the results.

Edge effect may be reduced to some extent by control of the electrode-edge curvature. We have also seen how an increase in the conductivity of the ambient medium minimizes edge-effect discharges. A third method is adjustment of the dielectric constant of the surrounding dielectric.

In order to suppress local breakdown of the ambient medium, the dielectric constant should be greater than that of the speci-

[1] *Elec. Jour.*, July, 1934, p. 324.

men under test. In this way, maximum stress is placed on the solid sample, and the medium prevents flashover and incipient discharges. This gives the desired result in most cases. A more exact treatment of the problem is given by Whitehead,[1] who concludes that the product (dielectric constant × dielectric strength) of the surrounding medium should be greater than the similar product of the dielectric being tested. This applies in particular when the two dielectrics are in series, a condition often existing at the curved edge of electrodes. Whitehead's time-

TABLE IV

Medium	Dielectric constant	Standard test-cup break-down, kv.	Resistivity at 200°C., ohm-cm.
Air	1.0		
Transformer oil	2.2	30 kv.	7×10^{12}
Inerteen (chlorinated fireproof liquid for capacitors)	4.7	40 kv.	3×10^{12}
Mixture (½ amyl alcohol; ½ transformer oil)	9.0	25 kv.	0.3×10^{12}

voltage curves on varnished cloth illustrate the effect of changing the dielectric constant of the medium (Fig. 33). For breakdowns occurring in a short time (up to 20 sec.) the curves all coincide; but at longer times (and lower voltages) there is a difference of over 25 per cent in favor of castor oil (also linseed oil) as compared with transformer oil or air. The two organic liquids have dielectric constants about double that of varnished cloth. It is to be noted that transformer oil (constant slightly less than varnished cloth) and air (half the value of cloth) give the same results. From this one would conclude that, if the medium has a lower constant than the specimen, it does not matter how low it is. A critical point occurs where the constants are equal, or, more exactly, when the constants × dielectric strengths are equal.

The author conducted tests on 0.010-in. varnished cloth, 0.015-in. mica plate, and 0.070-in. molded Bakelite to determine the effect of the dielectric constant of the medium. Four dielectrics were used. (See Table IV.)

[1] *Op. cit.*, p. 164.

The last liquid (amyl alcohol and oil mixture) has of course an increased conductivity as well as higher dielectric constant, but the test results fall nicely in line with the other data where conductivity was not a factor. Figure 34 was plotted from these test results. All curves show a definite increase in apparent dielectric strength with increase in dielectric constant. Even with three sizes of electrodes, the direct proportionality holds well, except perhaps for mica where the increase is not a straight line. These tests were conducted by the "minute-hold" method wherein the voltage is found at which the sample fails in 1 min. Tests made at shorter times (10 to 20 sec.) confirmed Whitehead's results, showing little effect of the medium.

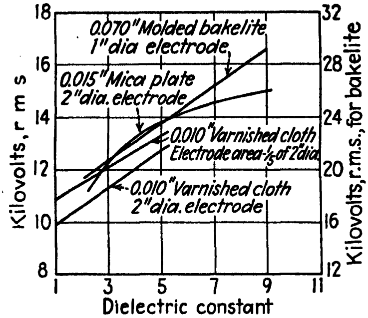


FIG. 34.—Effect of dielectric constant of ambient medium.

The time tests with high dielectric-constant media approached the values of short-time tests, a condition not true in using air or oil. With the latter, instantaneous breakdowns are usually much higher than time tests.

From a practical standpoint, it is difficult to obtain a satisfactory liquid medium of high dielectric constant. If the electrical properties are right, usually the chemical properties or perhaps the physical (viscosity) are unfavorable. For example, many of the liquids of high dielectric constant such as alcohols, tricresyl phosphate, nitrobenzene, and xylene are volatile or toxic or are good solvents for many of the materials being tested.

Summary.—As we have noted before, it is not easy to make a simple statement covering the behavior of dielectrics, even though the conditions are defined. However, some generalizations (to which exceptions can be found) may be helpful.

1. Gases and liquids behave more consistently in relation to changes in electrode structure than do solids.

2. Usually, the radius of curvature of electrodes is important. Larger radii reduce concentration of stress and produce higher breakdown tests than do sharp-edged electrodes.

3. Large-area electrodes give lower breakdown tests than do small electrodes. In some cases, needle points, in spite of the obvious stress concentration, exhibit higher test values than large-area electrodes. The explanation is based partly on the probability of weak spots and partly on the lowering effect of ionization at points of poor contact in the case of large surfaces.

4. Unless there is an abnormal heat-dissipation effect, the material and conductivity (thermal and electrical) of the electrodes are of no consequence.

5. In the testing of solids, an increase in the conductivity or dielectric constant (or both) of the surrounding medium raises the breakdown voltage, in some cases phenomenally.

CHAPTER IV

INSULATING MATERIALS

A description of all materials used for insulating purposes would assume handbook or encyclopedia proportions if comprehensive and complete. Our present treatment will be limited to presenting sufficient data about the major classifications of materials so that three questions can be answered:

1. What is the nature of the material?
2. What are its general properties?
3. For what is it useful in apparatus?

Where possible, certain materials will be compared, so that a rational choice can be made for specific conditions.

One method of listing materials would be alphabetically, which would facilitate reference; but the relationship between individual materials and groups is thereby lost. Another plan would be to group together all materials used in motors, in transformers, and in other apparatus. This would possess some merit, for each group would be a self-contained unit. The student would soon find, however, that he was reading the same material over and over, since there is marked similarity between insulating parts in various apparatus groups. It would, however, bring special emphasis to the point that the same type of insulating problem reappears frequently in somewhat different form and surroundings. By way of illustration, the insulation of a small motor coil has the same elements as the insulation of a waterwheel generator coil. A magnet coil is likewise the same device, whether it is part of a delicate relay or the solenoid of a large circuit breaker.

The author has chosen, however, to use another classification, grouping materials of similar nature or properties. Insulating papers will be discussed consecutively, all varnishes will be grouped, and plastics will be correlated, so that comparison will be facilitated. The following outline gives the order of treatment.

I. Gases:
   A. Air.
   B. Carbon dioxide.
   C. Nitrogen.
   D. Hydrogen.
   E. Rare gases (xenon, argon, krypton, helium).

II. Liquids:
   A. Mineral oils.
      1. Transformer oil.
      2. Circuit-breaker oil.
   B. Fireproof liquid dielectrics.
      1. Pyranol.
      2. Inerteen.
      3. Dykanol A.
   C. Vegetable oils.
      1. Tung.
      2. Linseed.
      (Castor oil, pine oil, and others are used in insulating varnishes or in binders for built-up insulation.)
   D. Solvents (not used as insulation directly, but in insulating varnishes and compounds; characteristics are therefore important).
      1. Alcohols.
      2. Toluene.
      3. Benzene.
      4. Benzine.
      5. Turpentine.
      6. Petroleum.
      7. Naphtha.
      8. Amyl and butyl acetates.
      9. Carbon tetrachloride.
      10. Acetone.

III. Solids applied as liquids, *i.e.*, melted, dissolved, or in liquid suspension.
   A. Gums or natural plastics.
      1. Fossil.
      2. Vegetable.
      3. Asphaltic.
      4. Shellac.
      5. Coumarone-indene.
   B. Waxes.
      1. Beeswax.
      2. Mineral.
      3. Chlorinated.
      4. Paraffin.
   C. Varnishes and lacquers.
      1. From natural gums and oils.
      2. From synthetic resins.
      3. Hybrids.
      4. Spirit varnishes.

5. Wire enamel.
6. Solvent varnishes.
7. Lacquers.

D. Synthetic resin (plastics—molded and laminated).
1. Phenolic (phenol or cresylic acid with formaldehyde or furfural).
2. Urea formaldehyde and urea furfural.
3. Resorcinol formaldehyde.
4. Vinyl copolymers.
5. Casein.
6. Acrylic.
7. Styrene.
8. Alkyd.
9. Maleic.
10. Rubber.

E. Cellulose compounds (thermoplastics).
1. Cellulose acetate.
2. Ethyl cellulose.
3. Nitrocellulose.
4. Cellulose acetobutyrate.

F. Cold-molded plastics.
1. Portland cement and filler } impregnated with resins or asphalts.
2. Calcium silicate and filler } impregnated with resins or asphalts.

IV. Solids:

A. Mineral.
1. Quartz.
2. Soapstone.
3. Mica.
4. Marble.
5. Slate.
6. Asbestos (see also under Fibrous).
7. "Alsifilm" (bentonite).

B. Ceramic.
1. Glass (see also under Fibrous)
2. Porcelain.
3. "Mycalex" (inorganic thermoplastic).

C. Lastics.
1. Natural rubber.
2. Gutta-percha.
3. "Koroseal."
4. "Thiokol" (Ethylene polysulphide).
5. "Neoprene."
6. "Buna."

D. Fibrous (untreated and treated).
1. Cotton (yarn, cloth, twine, fiber).
2. Silk (yarn and cloth).
3. Linen (twine and cloth).
4. Hemp (paper and fiber).
5. Paper.

6. Glass (yarn, cloth, and mat).
7. Asbestos (fiber, paper, and cloth).
8. Wood (natural).
9. Cellophane.
10. Rayon.
11. Nylon.

Before we commence on the list outlined above, a few generalizations can be made which will help the reader to keep the proper perspective.

1. Most of the useful insulating materials have a natural organic origin, either recent as in cotton, in the recent past as in wood, or ancient as in petroleum oil. From this, it follows that, in spite of refining, blending, or selection, these products have the inherent variabilities of nature's handiwork. Further, they are mostly subject to time changes, usually for the worse, as a result of oxidation or other chemical reactions. Some of the synthetic materials (*e.g.*, resins), though derived from organic materials, are nevertheless more subject to control.

2. No practical insulation even approaches an ideal material. Weaknesses of one kind or another are frequent. Take two examples: Porcelain is a high-quality dielectric, electrically and chemically; but its mechanical properties leave much to be desired. Rubber has admirable chemical, mechanical, and electrical characteristics at first inspection. But we discover certain faults. As usually compounded in wire coverings, it is not completely waterproof. It will deteriorate in oils and is ruined mechanically by high-voltage corona (an oxidation process).

3. Rarely do we require insulation with the highest electrical properties—meaning high dielectric strength, low losses, high resistivity. We are usually satisfied with much less than perfection in electrical properties. This is not altogether a complacency born of long and disappointing experience. The best would be "none too good." If a high-electric-strength dielectric were available, everything could be made smaller, lighter, cheaper. But this is a forlorn hope as long as the required improvements in mechanical and chemical attributes are not coincident. Thinner coil insulation for motors would avail nothing unless it were equally tough, to withstand machine and human abuse during manufacture and later the rigors of vibration and temperature changes.

There are exceptions to the foregoing statements. For example, high-voltage apparatus demands the best we can devise. This narrows our concern for maximum electrical "quality" to certain parts of transformers, switchgear, lightning arresters, turbogenerators, and cables.

GASES

Gases are common and very useful dielectrics. Though there is little to choose among different gases for electrical properties at normal pressures, there are differences in chemical or thermal characteristics that determine their choice for specific purposes. These differences among gases, though measurable, are still not of the order of magnitude noted with liquid or solid dielectrics. Electronic devices are built around the conduction of electricity through gases, rather than the insulating value; but this vast subject of gaseous conduction is not part of our present subject. Our present interest is confined to the uses of gases as insulating media.

Although gases do not possess exceptional dielectric strength (the maximum breakdown of normal air is 31 kv. crest per centimeter), they do have fortunate electrical attributes in other respects. For all practical purposes, dry and un-ionized gases have infinite resistance and zero dielectric loss. This is something that cannot be said for any liquid or solid materials. Where there is plenty of room to provide distance between parts, gases (air, in particular) afford admirable insulation. In general, they are poor conductors of heat, however, and are thus ineffective in removing losses in electrical machinery, unless in forced rapid motion. Another fault is that air (or any gas) is obviously deficient as a mechanical support. Coils will not hold themselves apart in air. It follows, then, that in gas-insulated structures, the determining problem will often be the mechanical connectors that must replace the gas at necessary points of support, rather than the design of the gas spaces themselves. In high-voltage apparatus in air, we find that the question of creepage over the surface of solid supports is the vital one and that it may dictate spacings greater than would be required for undisturbed air.

Dielectric constants of common gases are all substantially the same at atmospheric pressure as a vacuum. They are all slightly above unity, but for most gases by less than 1/10 per cent.

Table V

Gas	Dielectric Constant
Air	1.0006
Carbon dioxide	1.001
Hydrogen	1.0003
Argon	1.0005

With increase in density, the dielectric constant of gases increases appreciably. For each gas, an expression for the constant in terms of temperature and pressure can be derived. The change in the case of air is linear, reaching 1.05 at 100 atmospheres.

There is much more difference among gases in respect to dielectric strength than dielectric constant. Calling air at atmospheric pressure unity, the dielectric strength of oxygen is 0.95, nitrogen 1.16, carbon dioxide 1.20, and hydrogen 0.87. Pressure increases are accompanied by roughly linear increases in dielectric strength up to perhaps 10 atmospheres. This property is used in compressed-gas insulation in enclosed vessels, such as capacitors. In high potential chambers such as "atom smashers," compressed air serves to increase the permissible voltage attainable.

Air

Air might be called the universal dielectric. It appears as an insulator in parallel, at least, in all devices. If high local gradients are prevented, air is reliable and satisfactory for many purposes as the major insulation. Air-break switches, small and large, are examples of this use. In high-voltage insulating parts, the major insulation is at some point in contact with air. The contour of the surface then must be proportioned to disturb the dielectric field as little as possible, or else long "creepage" paths must be provided. The latter is usually the aim in insulator design, for the effects of surface dirt and moisture are the determining factors.

Air in series with a solid dielectric, at high voltage, should be avoided. The difference in dielectric constants throws the stress mostly on the air and causes corona or local breakdown. Precautions are taken particularly in generator and transformer construction to eliminate the possibility of air pockets.

Carbon Dioxide

This gas at reasonable temperatures is quite inert and therefore harmless to surrounding insulating and conducting materials.

It has somewhat higher dielectric strength than air and is useful as a compressed-gas dielectric. High-voltage, low-loss capacitors for measurement standards often contain carbon dioxide. Its higher density (than air) is of importance, also. It can be used with only slight confining means as a fire protection blanket. The carbon dioxide fire extinguishers are particularly recommended for electric apparatus because the gas will not injure insulation or form a conducting path from "live" apparatus to the person fighting the fire. Another use is as a protective gas covering for tanks of varnish, gum, or other organic impregnating compounds. Most other gases will cause deterioration of organic compounds if in contact with the surface for a long time at high temperature. Explosions may occur if compressed air is used in impregnation with volatile materials. Carbon dioxide is manufactured by the burning of coke and by vegetable fermentation. This gas could be used for an atmosphere in transformers except for possible trouble from the freezing of reducing valves on tanks of compressed gas.

Nitrogen

For an inert atmosphere above the oil in transformers, nitrogen is used. It prevents absorption of oxygen by the oil, which causes formation of organic acids and sludge (see Behavior of Oil in Transformers, p. 79). Nitrogen can be obtained from air by removal of the oxygen. Relatively pure gas is thereby obtainable, which accounts for the original and continued preference for nitrogen in transformers instead of carbon dioxide.

Another important use is in electric lamp bulbs. Here the function is mainly to reduce evaporation of the filament and thus prevent blackening of the bulb, which is a serious problem with high-wattage lamps. Convection currents in the nitrogen remove the evaporation products to the base of the lamp, where the effect is least objectionable (see Lamps, Chap. XV).

Hydrogen

This gas cannot be considered the best in dielectric properties, but it has one remarkable characteristic—a phenomenal heat conductivity, 7½ times as great as air. As a gaseous heat remover, therefore, it is very valuable. The chief application at present is in cooling rotating electric machines. Many kilovolt-

amperes of hydrogen-cooled generators and synchronous condensers are in operation. In such designs, the machine is completely enclosed, sometimes in a cylindrical tank, and hydrogen atmosphere circulated through the machine and to an external heat exchanger. Care must be taken to preserve a positive outward pressure, so that the possibility of explosive mixtures with air will be avoided. Hydrogen is sufficiently inert so that usual insulating materials are less affected than in air. At high voltages, corona appears in hydrogen at 60 per cent of the gradient that it does in air. Such a characteristic might seem serious, except for the fact that corona in hydrogen is less "vicious" and with no oxygen present does not form chemical products which attack insulation.

Another advantage of cooling by hydrogen arises from its low density, which is 7 per cent that of air. High-speed machines benefit by a great reduction in windage losses, proportional to the comparative densities, when hydrogen replaces air. Hydrogen is produced commercially by several methods, a common one for "bottled" gas being the electrolysis of water.

Rare Gases

Air contains small quantities of xenon, argon, and krypton, which are high in atomic weight and have sufficiently low thermal conductivity to make them valuable as constituents of gases used in electric lamps of the filament type. Helium, having high thermal conductivity, has special uses involving this property, discussed under Lamps, Chap. XV. Helium is obtained from certain natural gas wells.

LIQUIDS

Mineral Oils

Petroleum oils were in use as liquid dielectrics very early in the history of electrical apparatus. A dual function has always been performed by oil, *viz.*, insulation (oil being an ambient medium of electric strength greater than air) and heat conduction. Immersion of a device such as a transformer in such a liquid medium allows distances between parts to be decreased, and the whole assembly in a tank of oil is protected electrically from surrounding objects. For such a purpose a heavy oil of good electrical property would be satisfactory. One might even sug-

gest that a gumlike material, solid at room temperature, would do. Such an embedding of a transformer in a solid would suffice electrically, except for one advantage of oil (or a similar liquid medium)—the fact that it is self-healing. A surface failure of apparatus caused by an accidental momentary overvoltage might be cleared by a liquid medium which flows to the break to reinsulate the path. Let us examine the other duty of a liquid dielectric—the dissipation of heat. Losses in apparatus, whether resistance losses, iron losses, or dielectric losses, must be conducted away and removed as fast as generated, or an unstable temperature condition will develop. Air, especially in restricted spaces, is not a good means for this purpose. A liquid of high heat conductivity and low viscosity is preferable. Thermal gradients in the container will establish useful convection currents which will carry heat away from the source.

Why was a light petroleum oil chosen as a desirable insulating liquid? This question can be answered by reviewing and eliminating the other possibilities. First, any liquid miscible with water or having any affinity for moisture would have to be ruled out. Alcohols would thereby be eliminated. Many solvents, including benzene (benzol), toluene, gasoline, and ether, are good dielectrics, but their volatility is too high. Evaporation would produce flammable or explosive gases. Carbon tetrachloride was seriously considered at one time, but it is corrosive to copper in the presence of slight moisture contamination and produces toxic gases when decomposed by heat. Vegetable oils are unstable, becoming rancid with time. Finally, one factor that is perhaps most decisive is cost. Excellent mineral oil can be obtained at an attractive price (around 20¢ per gallon).

Keeping in mind the requirements to be met and the outstanding defect of petroleum oil, its fire hazard, where in the range from high-test gasoline to thick cylinder oil shall we select the best combination of properties? We must have a liquid that is limpid, yet with high flash and flame test. The specific gravity must be sufficiently different from water so that any accidental moisture will settle out easily. There must be a high degree of stability at operating temperatures so that "sludging" may be avoided. Overrefined oils designated as "water-white" are not desired because of the tendency toward formation of organic acids.

The two major uses of petroleum insulating oil are in transformers and circuit breakers. Oil also appears as the liquid insulation in induction regulators, capacitors, contactors, and switches. At one time, engineers asked that oil for a circuit breaker should have characteristics different from those of oil for a transformer. It was thought important to have a low cold-pour test for switch oil, so that the liquid would flow during opening of the switch in cold weather. Since transformers develop core loss heat, a low pour test was not necessary; in fact, early transformer oils were like petroleum jelly at low temperatures. In switches, finely divided carbon is produced by the arc. Such carbon particles should be readily thrown out of suspension and should be a minimum in volume. Switch oil must have a specific gravity conducive to carbon settling to the bottom and must have a chemical structure not subject to easy carbonization by arcs.

It was recognized years ago that the requirements of circuit breakers and transformers for an insulating oil were not incompatible. An oil good for both uses would certainly be desirable from the user's standpoint. Only one oil would then have to be carried in stock, and there would be no danger of putting in the wrong oil or of getting the grades mixed. Universal oils, refined to combine the optimum properties, have become the rule.

Specifications.—A comparison of specifications for transformer oil and for circuit-breaker oil will show the essential absence of disagreement that led to the development of a common type.

For Transformers	For Circuit Breakers
1. High dielectric strength	1. High dielectric strength
2. No trace of acid from refining No alkali, no sulphur	2. No trace of acid from refining
3. Low viscosity for effective heat transfer	3. Low viscosity to cool arc with fresh oil
4. High resistance to emulsion (water will be thrown out)	4. High resistance to emulsion
5. Low specific gravity (water will settle)	5. Low specific gravity (water kept out of contact area)
6. Freedom from sludging	6. Low formation of carbon in arc

Behavior of Oil in Transformers.—The principal causes of deterioration of insulating oil in service are water and oxidation. The oil may be exposed to moisture through condensation from moist air due to breathing of the transformer, especially when the

transformer is not continuously in service. The moist air drawn into the transformer condenses moisture on the surface of the oil and inside the tank. The oil may also be contaminated with water through leakage, as from leaky cooling coils or covers. These sources of water contamination are practically eliminated in modern transformers equipped with dry-gas atmosphere or with expansion tanks. Sludge is an oxidation product, the amount formed in a given oil being dependent upon the temperature and the time of exposure of the oil to the air. By careful refining, the components of oil that are most readily oxidized to

TABLE VI.—SPECIFICATION FOR REPRESENTATIVE INSULATING OIL

Specific gravity	0.898 at 15.5°C.
Viscosity (Saybolt)	57 sec. at 40°C., 280 sec. at 0°C.
Pour test	−45.6°C.
Neutralization value	0.03 mg. of KOH per gram
Demulsibility	25 sec.
Flash point	132°C.
Fire point	149°C.
Color	Very pale yellow (almost water-white)
Dielectric strength	30 kv. minimum (0.1-in. gap in standard test cup)

form sludge can be removed, so as to provide an insulating oil that will not sludge for a long period under normal operating conditions. Excessive temperatures, however, may cause sludging of any transformer oil, regardless of how well it is refined.

Transformer oil that has begun to sludge will continue to do so after it has been purified by means of the centrifuge or filter press, for these methods of purification do not remove the deterioration products that are in process of formation but have not yet been thrown down as sludge. No method is yet available in the field that will remove these products and bring sludged oil back to its original condition. Such oil can be refined so as to be equivalent to new oil, but this would require equipment which is available only in an oil refinery. It is not economical to send used oil to the refinery; for it will allow only the fuel-oil price, and this would probably be less than the cost of transportation.

Another effect of oxygen is gradually to produce organic or "fatty" acids in oil in service. There is no method available in the field for purifying oil of high organic acidity.

In an effort to produce oil that has less tendency to sludge, it is possible to "overrefine" it. Such an oil develops organic acidity,

which, when once started, increases rapidly to a point where it becomes a menace to insulation.

Behavior of Oil in Circuit Breakers.—The principal causes of deterioration of insulating oil in circuit breakers in service are: (1) water; (2) carbonization of the oil caused by operation of the circuit breaker.

Insulating oils do not absorb water in appreciable quantity, but they may receive water through condensation on the surface of the oil or on the inside of the tank, owing to the entrance of moist air.

All oil in circuit breakers is subject to carbonization due to arcing between the contacts. Part of the carbon formed is deposited on the mechanism and at the bottom of the tank, and the remainder continues in suspension in the oil. Carbonization takes place not only when the circuit breaker opens heavy short circuits but also whenever an arc is formed, even during such light service as the opening of the charging current of the line; the latter service repeated may eventually produce enough carbon to be a source of trouble.

The carbon reduces the dielectric strength of the oil, lowers the surface resistance of the insulation if water is present, and also lowers the resistance to emulsification. It may not be detected by the dielectric test, particularly if the oil is free from moisture.

In cold weather, a larger amount of carbon is formed than in warm weather on account of the increased viscosity of the oil at low temperatures. Also, the carbon is not so readily dispersed through the oil.

Purification of Used Oil.—The purification of oil used in circuit breakers and transformers consists principally in the removal of water, carbon, and sludge and the restoration of its resistance to emulsification, putting the oil in the best condition to separate out any water that may later be introduced.

Three types of equipment for simple purification of oil in circuit breakers and transformer service are in general use: the blotter filter press, the centrifuge, and the combination centrifuge and filter press.

Blotter Filter Press.—The filter press is essentially a number of sets of filter papers in parallel, each set containing several thicknesses. The oil is pumped through the filter paper, which absorbs the water and strains out the sediment.

The filter press is not intended to remove large amounts of free water from the oil. Obviously the changing of filter papers necessary for obtaining dry oil would take so much time as to make this method of purification impractical. In such cases the water may be removed by a centrifuge or should be allowed to settle out and be drawn off from the bottom of the container before passing the oil through a filter press.

With badly fouled oil, it may be necessary to pass the oil several times through the filter press to take out the more finely divided carbon which is not caught on the blotters, especially when they are new. The efficiency of the filter press for removing carbon increases as the pores of the blotters become partly clogged. This produces a definite slowing down in the rate of flow through the blotters.

Filtering through blotters does not materially reduce organic acidity or improve resistance to emulsification, except as the latter is affected by the presence of carbon, although the dielectric strength may be restored to a satisfactory value.

CENTRIFUGE.—This is the most convenient equipment known for removing water from oil. It also removes solid material other than finely divided carbon. The centrifuge equipment may be arranged to act as a separator, discharging the oil and water by different outlets, or as a clarifier, discharging the oil but retaining, in the bowl, water and other impurities. When there is considerable water in the oil, the centrifuge equipment should be operated as a separator.

The centrifuge will remove the coarser particles of carbon from the oil. For removal of fine particles of carbon, the blotter filter press or the centrifuge supplemented by suitable chemical treatment (sodium silicate and diatomaceous earth) should be used.

Soluble impurities developed by constant use of the oil in circuit breakers or transformers can be removed only by *chemical treatment.*

COMBINATION CENTRIFUGE AND FILTER PRESS.—This device meets the need for a compact unit that may be used advantageously in the purification of insulating oil. Briefly, it consists of a motor-driven centrifuge, electric heaters, regulating float valve, pumps, and filter press or presses, mounted upon a truck (Fig. 35).

Summary.—The relative advantages of insulating-oil purification processes are as follows:

The centrifuge connected as a separator may be used where there are large quantities of water present in the oil, without waiting for it to settle out; connected as a clarifier, it may be used for removing small quantities of water. It will remove sludge and coarse carbon particles, but not all finely divided carbon.

Fig. 35.—Combination centrifuge and filter press for purifying insulating oil. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The filter press is suitable for use for the purification of oil containing small quantities of water and will remove finely divided carbon and sludge. It will not materially reduce organic acidity or improve the resistance to emulsification, except as this is caused by the presence of carbon.

The combination centrifuge and filter press may be used advantageously in the removal of large quantities of carbon and water. It unites the exceptional qualities of the centrifuge with the excellent characteristics of the blotter filter press. This flexibility of operation makes it very desirable as standard equipment in the reconditioning of insulating oil for the removal of

large quantities of carbon from the oil. The clogging of the pores of the filter reduces the output of this combination.

Purified oil should have minimum properties as follows:

Dielectric strength	22 kv. for standard test cup
Demulsibility	35 sec.
Neutralization	0.08 mg. KOH per g. of oil

Fireproof Dielectrics

There has long been a need for a liquid dielectric that does not present a fire hazard. To one not knowing the background of the use of petroleum oil in transformers and circuit breakers, it would seem absurd to use such a flammable material. The interruption of an arc in a circuit breaker under oil seems particularly disadvantageous. It is a wonder that oil serves at all successfully.

A failure leading to short circuit in a transformer does not often develop suddenly. Turn-to-turn or turn-to-ground arcs are established with an initial relatively high resistance path, so that the circuit is not opened by the usual relays and switches. This sort of breakdown is often called a "stewing arc" and if continued will result in a phase-to-phase or phase-to-ground arc where considerable power is released. Gas is evolved from locally heated oil; and sometimes, in spite of safety devices, explosions and fires result. Such accidents are rare; but in crowded cities, especially where transformers are used in street and building vaults, they do enough damage to justify a serious search for liquids better than oil. Outside its fire hazard, the properties of oil are admirably suited to both transformer and circuit-breaker functions. It has low viscosity and good cooling and is chemically inert to most insulating materials. Since oil is a rather poor solvent, there is no difficulty in obtaining satisfactory insulating varnishes and gums necessary for transformer construction. A substitute, therefore, should have all these virtues plus fireproofness.

Chemists have long known the fire-resisting and -extinguishing properties of chlorinated compounds. In fact, carbon tetrachloride and related compounds were seriously considered for a transformer liquid. The objections were high cost, corrosive action of hydrochloric acid resulting from water contamination, and high volatility. Moreover, when decomposed by heat

carbon tetrachloride evolves toxic gas. But in spite of the rejection of carbon tetrachloride, it is recognized that chlorinated compounds appear to have the best possibilities as fireproof dielectrics. In view of the required stability of such dielectrics, chlorine derivatives of aromatics were found to be much better than those derived from the paraffins.

Development by the Swann Chemical Company of a series of chlorinated diphenyls known as Aroclors gave an impetus to the research that was in progress in several commercial laboratories. Aroclors by themselves have unfavorable physical characteristics for transformers but are now used widely in capacitors, partly for fireproofness, but largely because of the high dielectric constant (see Capacitors, Chap. XIII). The trade names under which Aroclor for capacitors is sold are Pyranol, Inerteen, and Dykanol A. Blends with other chlorinated compounds were developed, and liquids for transformers are now in successful use, consisting of chlorinated diphenyl combined with trichlorbenzene, chlorinated ethyl benzene, chlorinated naphthalene, or other similar liquids. These combinations are not perfect, and the search is going on for better combinations, particularly with respect to improved physical characteristics and reduced cost.

The present transformer dielectrics, Pyranol and Inerteen, are high in cost. They develop hydrochloric acid when decomposed by heat or by arcing and are solvents for almost all the usual insulating varnishes, compounds, and finishes. However, they do not support combustion and in fact are good fire extinguishers. Special insulation to resist the dissolving action is required.

Chemically, the fireproof transformer dielectrics are stable materials at room temperature. They are very resistant to oxidation and do not sludge or develop acidity like the hydrocarbon oils. In this respect, they are ideal coolants for transformers.

The general properties are

Flash point	None
Fire point	None at boiling
Specific gravity	1.5
Viscosity (Saybolt) at 100°F	50 to 55 in.
Decomposition temperature	Above 300°C.
Color	Number 1 union colorimeter (same as transformer oil)
Pour test	−30°F.

Because of the unfortunate products of decomposition in an arc, none of the chlorinated materials can be used for circuit breakers. The present trend in this field is a radical reduction of the amount of oil used (oil-poor breakers) or else the use of gases, sometimes compressed. In Europe, some progress has been made with a device interrupting arcs in water.

Vegetable Oils

There are several oils of plant origin that find use as or in insulating compounds. The more common are tung, linseed, cashew-nut, castor, and pine. These are generally employed as ingredients in varnishes, bonds, or compounds; but the first two are sometimes used alone for the impregnation of wood and cotton. They have the advantage of good penetration plus a fair surface moistureproofing. Varnishes can be applied after such impregnation, if a smooth surface is desired.

Tung oil is derived from the three-lobed nut of a tree native in China, from which most of the oil comes. Plantations of tung (China-wood) trees are now flourishing in some southern states, reporting yields far in excess of Chinese trees; but so far the total production is only a small fraction of the requirements of paint and varnish manufacturers.

Linseed oil is pressed from flaxseed. Seed is imported from the Baltic countries, India, and Argentina. Crushing, cooking, and refining are performed in the United States.

Cashew-nut oil, a relatively new product, is compounded with other oils in the manufacture of certain varnishes that have unusual toughness in films and impregnate with a minimum of solvent.

Castor oil and **pine oil** are representative of the "nondrying" oils and find use as plasticizers in bonds for flexible mica sheet for molding purposes.

Solvents

Under this heading are included both true solvents and diluents. The latter may be defined as a liquid that is not very active in dissolving solids (such as resins or gums) but is useful in changing the physical properties, such as viscosity, of solutions, so that application is made easier. A descriptive term for a diluent is a "thinner."

Most solvents serve the purpose of carrying insulating solids to the point of use, as varnish into a wound coil. Subsequently the solvent must be removed, and this problem is not always a simple one. Practically, residues of solvent may remain in deep coils for a long time, even months. The insulating properties of solvents are therefore of interest. Fortunately, most usual solvents, unless contaminated, are good insulators as liquids and do no harm in insulation from an electrical standpoint. Exceptions are the solvents that are miscible with water and for that reason may be poor dielectrics. The alcohols (ethyl, methyl, amyl, etc.) are examples. It is important to remove thoroughly all traces of such solvents because of the danger of water absorption. Lacquer thinners, such as amyl acetate and butyl acetate, are sufficiently volatile to cause no serious concern. Carbon tetrachloride, when pure and free from water, is a good dielectric. Its decomposition by heat releases phosgene ($COCl_2$), a toxic gas.

Certain of the most active solvents, such as benzene (benzol), toluene, and carbon tetrachloride, have unfortunate toxicity and have to be used with care. Ample ventilation is essential in any case, but such solvents are to be avoided if possible because poisoning through skin contact is also possible. For some necessary materials such as phenol resins, benzene (not benzine) still seems necessary and is used with precautionary protection for workers.

Petroleum solvents (naphtha, gasoline, kerosene) and turpentine are good insulators, and complete removal is not essential for electrical properties.

SOLIDS APPLIED AS LIQUIDS

Gums and Natural Plastics

"Fossil" gums occur in tropical countries as deposits formed in prehistoric times from vegetation then extant. Typical of these are dammar, acroides, and copal. They are all used in the manufacture of varnishes, the last two named being useful in shellac mixtures. Copal, although not possessing the adhesive strength of shellac, has favorable flow properties and is used to maintain this characteristic in shellac compounds. Bonds for sticking mica contain copal with shellac. The fossil gums inherently vary in quality and have to be blended or modified to give uniform behavior.

Vegetable gums are the present-day products that are analogous to the fossil gums formed in bygone ages. Most of the common varieties come from trees, particularly conifers. Rosin and pine tar are examples. Rosin appears as an ingredient in shellac mixtures to improve flow and also in impregnating compounds. Pine tar, resulting from the distillation of yellow pine, is "nondrying" in that it is always plastic and is therefore valuable in flexibilizing impregnating mixtures which must always be somewhat pliable.

Impregnating gums are usually mixtures of several ingredients. Oilproof varieties are usually brown or amber in color and may contain fossil gum (copal), vegetable gum (rosin), and some flexibilizer such as castor oil or pine tar.

Asphalts may be taken from natural deposits (Lake Trinidad) or may be the residual product from distillation of coal or refining of petroleum. Asphaltic gums are blended with oils or other gums to produce impregnants giving excellent moisture protection. They are also unaffected by usual alkalies and acids. Most asphaltic compounds, however, are soluble in petroleum oils and therefore are useless in transformers operated under oil. For air-insulated magnet coils and transformers, they are excellent for protection and removal of heat. It is possible to produce reasonably oilproof asphaltic compounds, but in general continuous immersion in oil is not recommended.

Shellac can be classed as a gum in that it is a solid, resinous natural deposit. It is used in alcoholic solutions as a finish, and as an adhesive. As a gum, it is blended with other materials for impregnation purposes. Further, it is a plastic appearing with various fillers as a molding material.

Shellac is formed by exudation from certain varieties of licelike insects that suck the sap of certain Indian trees and cover themselves with a coating of resinous material. Shellac varies widely in color and consistency, being influenced by climatic changes, type of tree used as host, and the state of health allowed to the insect by its natural parasitic and predatory enemies.

As first gathered, shellac is called "stick-lac" and contains twigs, insects, and lac. Purification is required. It consists of washing the ground stick-lac and removing foreign matter along with red coloring known as "lac dye." The product is then designated as "seed-lac," because of its shape. Light-colored

large particles are classified as orange shellac. The dark smaller granules become lower grades of orange and garnet shellac.

The major property by which shellac is judged (other than freedom from dirt, dye, and wax) is the flow or fluidity. Some commercial grades differ from others, and most change with time and humidity. Storage conditions are therefore important. Long exposure to heat will reduce the fluidity of melted shellac. Often, such shellac can be reclaimed by blending with very fluid varieties.

One flow test consists of measuring the time taken for 2 g. of melted shellac held at 125°C. to run down a 60-deg. incline a distance of 5 in. Commercial grades and values for this test are as follows:

Grade	Time, Sec.
V S O orange	60 to 100
Pale orange	80 to 200
C V T N orange	100 to 200
Garnet	200 to 1,500

Another important test for shellac is the life test (also called the polymerizing test), which is an indication of its progress toward an infusible and unworkable state. It is performed by observing the time taken at a high temperature (125°C. usually) for the melted shellac to reach a "rubbery" stage. Average values are

Grade	Time, Min.
V S O orange	60
Pale orange	50
C V T N orange	35
Garnet	20

As an impregnating or coating material, with or without fillers, shellac is very desirable from certain angles. It is hard and tough, resists carbonization of electric arcs on the surface, and has good power factor if the solvent is completely removed. Its chief weakness is solubility in alcohols and alkalies. The excellent adhesive properties are particularly valuable in formulation of cements and bonds. For the former, fillers such as powdered mica, iron oxide, and silica are useful. Many mica products are built up with adhesives made largely of shellac. Dry, powdered shellac, without solvent, is often used as an adhesive, being made

active by application of heat and pressure. In spite of the growth of the synthetic resin plastics, shellac is still used in tremendous quantities for electrical insulation.

In addition to their use for impregnation, coating, and similar purposes, gums and natural plastics are useful as bonds or cementing ingredients in certain grades of molded products. When mixed with fillers such as mica flakes or powder, asbestos, or silica, they can be molded at moderate temperatures (usually below 100°C.) into terminal blocks, switch bases, knobs and handles, and many other relatively small low-cost parts.

Coumarone-indene resin is a natural thermoplastic in the sense that it occurs in coal-tar naphthas (boiling range 150 to 200°C.), rather than being a reaction product of two or more materials. The liquids obtained by tar distillation contain a mixture of these two similar components, which by treatment are polymerized to a useful resin form. The properties that seem favorable are exceptional resistance to water and salt and alkali resistance. Although the more important uses of this series of resins are for floor mastics, linoleum cement, and chewing gum, electrical applications are also found. Rarely are these resins used alone, since the physical properties, such as brittleness, are not so good as in some other resins. The ready moldability, gloss, and chemical inertness are utilized in blends with alkyd and phenolic resins, natural waxes, pitches, and rubber. Coumarone-indene resins are also found in paper-waterproofing mixtures and as a moistureproof ingredient for Portland cement or asbestos-molded products. One common application is as a bond for molding carbon brushes.

Waxes

Waxes are useful for impregnation of other insulation, particularly in coils, and for treatment of wood. A few waxes, notably beeswax, have an animal origin, but most are mineral products. Most have excellent water resistance, high dielectric strength, low power factor, and high volume resistance; but practically all are oil soluble. Their use, therefore, is confined to coils or parts in air. One very desirable property possessed by waxes, and gums as well, is the transition from the solid to the liquid state and back again at temperatures convenient for fabrication, yet far enough above room temperature to be safe under operat-

ing conditions. In general, waxes have lower melting points (below 100°C.) than gums and also more sharply defined melting temperatures. Waxes pass abruptly from the plastic solid condition to a very limpid fluid. This makes them suitable for coil impregnation where high temperatures are not present or permissible and where thorough penetration is required. Waxes do not become hard and brittle, like most unmodified gums, which may or may not be an advantage.

The more common insulating waxes are those described below.

Beeswax is the secreted wax of bees, used for construction of the honeycomb. At 15°C. its density is 0.96 and its melting point 62°C. Because of its low power factor and high moisture resistance, it has been widely used for radio coils. Rarely is beeswax used alone. It is usually mixed with other waxes or with rosin to obtain desired physical characteristics.

Mineral wax (from distillation of petroleum) is frequently used as a substitute for beeswax, having quite similar properties. It is never really solid but is plastic and nonrigid, unless blended with other materials.

Montan wax is derived from the type of coal known as "lignite." Its distinguishing property is fluidity above 80°C., and it is often used to help increase the fluidity of asphalt compounds. The applications are coil impregnation and impregnation of dry-type paper condensers.

Halowax, another condenser impregnant, is a chlorinated naphthalene and therefore flame resistant. Its dielectric properties are excellent. Another important use is in flame-retarding coatings for cable braids.

Paraffin is a familiar petroleum product with a relatively low melting point (50°C.) for most grades. It is of course not oilproof. The chief use is in moistureproofing of wood, fish paper, fiber, and cotton-insulated coils that are operated at low temperature. The impression is abroad that paraffin is not waterproof. In itself it is, but impregnation is rarely perfect enough to exclude all moisture.

For properties of insulating compounds, see Appendix A.

Varnishes

A varnish may be defined as a solution of gums (either natural or synthetic) in a vehicle composed of drying oils and/or volatile

solvents. There is no fundamental difference between common finishing varnishes and insulating varnishes. The latter are designed for specific effects, such as penetration, flexibility, adhesiveness, or resistance to oils or chemicals.

Paints and enamels are often associated with varnishes. They may be differentiated by the composition. Enamels are varnishes containing solid pigments. Paints have still more pigment and little or no resins or gums and usually contain drying agents to assist in oxidation of the oils.

Varnish made from **natural gums** and **oils** is the most familiar product. Many varnish gums are available, such as copal and dammar for clear varnishes or asphalt and pitches for black varnishes. The vehicle may be linseed oil or tung oil or a combination of the two. Varnish oils are "bodied" (partly oxidized and polymerized) by cooking, and the final product is a mixture of gums and modified oils. The final viscosity is adjusted by addition of *solvents,* usually benzene, petroleum naphtha, or turpentine.

A high oil content produces slower drying but longer life (*i.e.,* slower oxidation). A quick-drying varnish using natural gums and oils is obtained at the expense of toughness and long life at elevated temperatures. This statement, however, may not be true of varnishes made from synthetic resins. The hardening of conventional varnishes after evaporation of the solvent is largely a matter of oxidation and polymerization. The change in tung oil is mostly polymerization; with linseed oil, oxidation is predominant. In any case the action does not cease but continues with time, at a slower rate. Unfortunately, designers must face the fact that varnishes deteriorate with age, as is evidenced by loss of flexibility, gloss, and toughness.

Varnishes may be formulated for either air drying or baking by proper adjustment of the oxidizing agents. Air-drying varnishes are less hard, have less moisture resistance, and therefore are poorer insulating coatings. Baking varnishes are therefore preferred, but cannot always be used. For repair work or on assembled apparatus that cannot be heated, an air-drying varnish is necessary.

Insulating varnishes are used for several purposes: (1) impregnation of fibrous insulation; (2) treating insulating cloth or paper; (3) as a surface finish. In the first use, the impregnation of coils demands a varnish that penetrates easily and thoroughly, dries

without formation of harmful by-products, has a minimum of solvent to be removed, has adhesive properties for bonding wires together, and is a good dielectric. Sometimes, where motion or vibration of coils is expected, a flexible varnish that practically never hardens completely is used. This type is known as a "plastic" coil varnish. Inasmuch as the drying of deep coils is difficult and is often incomplete when the apparatus is put into use, it is essential that impregnating varnishes be good insulation when partly "wet." There has been a tendency toward using endless varieties of varnish, each aiming at specific properties. Although there are special problems justifying individual treatment, in general it is advantageous to choose the fewest possible varnishes. Manufacturing operations can then be standardized, stocks can be held to a minimum, and adequate competitive sources of supply are available. For practically all purposes, four varnishes of the gum and oil type are sufficient. These would include black air drying, clear air drying, black baking, and clear baking.

Treated cloth and paper are made with varnishes similar in character to those for coil impregnation. Since treatment is by a successive dipping and baking process performed as a continuous operation, air-drying varnishes are not required. The characteristics sought are flexibility, long life, absence of pinholes or other film defects, moisture resistance, and a maximum of dielectric strength (see Fibrous Materials, p. 124).

Insulating varnishes are also used as surface coatings or finishes on insulation or metal. Some of the properties contributing to their excellence as insulating varnishes also make them satisfactory finishes, where moisture resistance and ease of cleaning are sought.

Varnishes made from **synthetic resins** contain uncured resins in a solvent such as benzene (benzol). The varnishes described above have gums, oils, and solvents; but the synthetic varnishes are usually resins in solvent, without oil. They are used chiefly in the manufacture of laminated plastics. Fillers are impregnated with the varnish and dried, then formed under heat and pressure. The solvent is practically gone before the final polymerization operation commences.

To some extent, synthetic-resin varnishes are used for impregnation of coils, particularly for rotating machines. Subsequent baking produces a very rigid, hard, self-supporting structure that

resists centrifugal forces. This method of coil treatment goes under the name of "bakelizing," derived from long use of the original phenolic resin. Other plastics may serve equally well.

Combination Varnishes.—The search for improved moisture resistance, better life in unfavorable atmospheres, and a more uniform product has resulted in the compounding of oil-type varnishes from synthetic resins and vegetable oils. Many varieties are on the market, and the expected advantages have been realized. The only disadvantage is higher cost. Most high-quality varnishes now contain some synthetics; and if the price can be justified, the "hybrid" varnishes are preferable to the orthodox gum and oil types. Another advantage is the control of drying characteristics that can be "designed" into the material.

Spirit Varnishes.—Narrowly defined, a spirit varnish is composed of a natural gum such as shellac dissolved in a highly volatile solvent such as alcohol. Such varnishes may be used for a rapid-drying surface coating or for impregnation of fibrous material. Many laminated products in tube and plate form are made of paper coated with shellac solution, dried, and then pressed under heat. Spirit varnishes are generally low in flexibility but are good adhesives.

A logical extension of the definition can be made to include other useful liquids of similar character. Under this more liberal designation, we should include asphaltic varnishes of the japan type which are chiefly asphaltic gums dissolved in petroleum solvents. They may be air-drying or baking japans.

Similarly, the solutions of synthetic resins used in laminated products might be classified as spirit varnishes, if we allow the "spirit" to cover a wider territory.

Wire enamel is a special form of insulating varnish for application to copper wire. The problem of adhesion to metal is an important one. The composition of conventional enamels includes fossil gums and drying oils (less oil than in varnishes) in a coal-tar solvent. Several coats are applied to form the insulating coating. The requirements to be met are

1. Flexibility in withstanding bending and elongation.
2. Surface hardness to resist abrasion.
3. Good electrical properties.
4. Long life (must be still flexible after 6 months' storage).

5. Resistance to hot varnish and oil (for apparatus subsequently varnish-dipped or immersed in oil).
6. Uninterrupted film (no holes or gaps).

It is very difficult to obtain all these characteristics at one time. Much research therefore has been aimed at better wire enamels. Synthetic resins have long been tried (phenolics and others) with only slight improvement and at great increase in cost. Recent developments, however, have given us a new promising phenolic enamel and also successful copolymers of vinyl and other resin groups. Formex wire, marketed by the General Electric Company, is an example of the vinyl type.

The thermoplastic resins seem to open the way toward more reliable enamels for wire.

Solventless Varnishes.—It seems rather futile to put 45 to 60 per cent solvent in a varnish and then try to remove it after application. Engineers have hoped for a material having the advantages of gums and waxes combined with the qualities of varnishes. A varnish that could be used as a liquid and then be hardened in place without the benefit of air to oxidize it and without producing any by-products would be perfect. The synthetic-resin ingredients have been looked to, since polymerization can be produced by heat without the need of oxidizing air. But reaction products such as water are present which are worse than conventional varnish solvents.

To meet the need, "solventless" varnishes were produced. They are composed of gums or resins and oils with practically no solvent. At room temperature, they are quite viscous but at 40°C. are sufficiently fluid to penetrate coils. By control of the temperature a heavy coating can be applied to the ends of motor coils. Impregnation of magnet coils and motor coils with solventless varnish is commonly practiced. This type of varnish is not yet a complete answer, because of difficulty in securing penetration and hardening in deep coils. Vacuum and pressure methods help.

Lacquers were once considered solely as finishes. They are, however, useful as insulating coatings. The dividing line between lacquers and varnishes becomes less definite as more resins and solvents enter the field. Perhaps we can distinguish a lacquer by defining it as a solution of thermoplastic resins in highly volatile solvents of the ester and alcohol types, such as

amyl acetate. Many of the liquid elements used in lacquers are not true solvents, but only diluents. When the resins are in solution, these diluents may be used to decrease viscosity. They are often called "lacquer thinners."

Lacquers have high dielectric strength, but usually high power factor. They would not be useful, therefore, in high-voltage dielectrics where dielectric losses are important. As moisture-proof coatings, lacquers are applied to cotton sleeving, woven tubing, and coil coverings.

The solid constituents of lacquer (about 20 per cent) are left near the surface when applied to an absorbing material, such as cotton. Consequently, thorough impregnation with lacquer is not usual. It can be considered only a protective surface coating, having the advantage of very rapid drying.

Plastics

The term plastics is broad and may be used to cover any material that can be formed into a desired shape and then solidified. Under this definition, Portland cement is a plastic and so is chocolate candy. Many synthetic plastics, such as pyroxylin, are used for purposes other than electrical, and their uses as insulators may be only incidental. In fact, most plastics have multiple uses, some mechanical, some decorative, some chemical or electrical.

Types.—We shall limit ourselves to consideration of those materials which have insulating value and subdivide the subject for convenience into

Synthetic resins, which are chemical-reaction products of two or more substances, formed by heat and pressure.

Cellulose compounds, derived from treatments of cellulose fiber.

Natural plastics (see Gums and Natural Plastics), using products substantially as found in nature.

Cold-molded plastics, formed without heat.

The technology of the plastic industry is an important and interesting subject, the history of which has been made largely since 1920. A story of the details of the manufacture of resins and fabrication of molded products would be beyond our present plan. We shall, therefore, proceed to a limited discussion of the sources of the principal plastics, their chief characteristics related to electrical insulation, and their common uses.

Forms.—Most plastics appear in several physical forms, being fabricated as

1. Molded parts from powdered resin and filler.
2. Sheets, tubes, rods, or molded forms cast or extruded from resin without filler.
3. Laminated sheets or tubes from paper or cloth, resin treated.

The varieties are almost endless, even in one type of resin, depending on method of manufacture, subsequent treatment, and fillers used. To say that a synthetic resin product is Bakelite (to use a familiar name) is no more definite or accurate than to say that a forest is a group of oak trees. We might compare the whole field of plastics to the forest, in which there are oaks, pines, and maples; and under each species there may be several distinctive kinds. There was once more difference between the species of resins (*e.g.*, phenols, ureas, styrenes) than now. Modifiers and plasticizers have enabled the chemist to obtain more and more desirable properties and fewer limitations within each class. Now the choice of a resin is not restricted, for similar properties can be obtained with several.

A useful differentiation has been the segregation into thermoplastic and thermo-setting resins. The first include materials that soften under heat and harden on cooling, a repeatable cycle. Thermo-setting materials are thermoplastic originally, but continued heat destroys the fusibility, so that the resin is ultimately solid and no further heating will soften it. Common examples are celluloid (thermoplastic) and Bakelite (thermo-setting). Of late, however, this convenient classification has lost its validity. Each type can be modified to approach the properties of the other. Thermoplastics are available whose remelting temperature is high enough to justify calling the material practically infusible. Thermo-setting resins can be made to be more or less permanently plastic to a useful extent. All this does not make easy the task of an engineer in the selection of materials. He must rely on the advice of those experienced with plastics. Unless he has such an expert available for consultation, he might well prepare specifications of the performance needed and the price limitations to be met and then entrust to a reputable plastic molder the job of picking out the resin.

Molded Plastics.—The following table lists some of the common varieties of molded plastics.

TABLE VII.—MOLDED PHENOLIC PLASTICS, CLASSIFICATION, DESCRIPTION, AND APPLICATION
(See Appendix A for properties)

Material number	Color	Primary filler	Material cost ratio	Description	Application (typical examples)
Class I. General Purpose (Mechanical and Electrical)					
1	Brown	Wood flour	122 to 155	Good-quality finish possible, strong, hard	General purpose, maximum temperature 135°C. where property changes are not extremely important
2	Black	Wood flour	114 to 256	Black counterpart of 1	See 1
Class II. Heat Resistant					
3	Brown	Long asbestos	100 to 156	Finish fair with some asbestos particles showing. Maximum heat resistance approximately 150°C. Best general purpose asbestos grade. May be machined but hard on tools	Commutators, collector rings, line material, trip shafts, couplings, contactor parts. Outdoor service
4	Brown	Short asbestos	163	Similar to 3 except shorter fiber asbestos and mechanically inferior	Spacers, trip shafts. Suitable for preforming and low cost
5	Black	Long asbestos	85	Most heat resistant, withstanding 200°C. continuous service with minimum change	Breaker, contactor, and miscellaneous parts
6	Brown	Long asbestos	141	Suitable for complicated molding	Line material. Outdoor service
7	Brown	Short asbestos	122	Brittle, hard, difficult to drill. Withstands approximately 175°C.	Levers and other small parts. May be preformed
8	Black	Short asbestos and wood flour	85	Weaker than #3 but suitable for more complicated molding of intricate parts. Withstands 150°C. with but slight change in properties	Low-cost heat-resistant parts. May be drilled and machined more readily than other heat-resistant grades
Class III. Impact Resistant					
9	Black	Fiber	200	High impact suitable for complicated thick sections	Control bases

TABLE VII.—MOLDED PHENOLIC PLASTICS, CLASSIFICATION, DESCRIPTION, AND APPLICATION.—(*Continued*)

Material number	Color	Primary filler	Material cost ratio	Description	Application (typical examples)
10	Red	Fabric	225	Mechanically strong, appearance good, one of highest impact resistant grades	Motor housings, handles, clamps, frames, rocker rings
11	Black	Cotton fiber	250	Semi-impact material of good appearance and fairly low cost	Instrument cases and relay bases
12	Black	Cotton fiber	190	Similar to 11 but of lower cost and more suitable for complicated parts	Terminal blocks, handles, cams, spools, light sockets
13	Black	Cotton flock and wood flour	165	Lower impact than 12 but suitable for economical molding of small parts	Terminal angles and washers. May be preformed
14	Black	Paper pulp	200	Similar to 12 but of inferior finish	Fuse-tube nuts. Refrigerator bolts. May be preformed. Economically molded.
15	Black	Pulp board	235	Reinforcement material, adapted for special molding with large flat inserts	Jumper bars, miscellaneous reinforcements
16	Natural	Cotton cord	220	Tan to brown in color. Impact higher than 12 on standard specimen	Terminal brackets
				Class IV. Superior Electrical Insulation	
17	Tan	Wood flour	190	Tan to brown, properties similar to 1 except superior insulation up to 100°C.	Transformer parts. Do not use in combination with large inserts
18	Black	Mica	210	Low power factor, high surface and volume resistivity	Radio-frequency applications

FILLERS FOR MOLDED PLASTICS

I. Organic (cellulose):
   A. Powdered or short-fiber fillers.
      1. Wood flour. Low cost and has good molding quality.
      2. Cotton flock } Increase the impact resistance as compared with
      3. Paper pulp } wood flour.
   B. Coarse or long-fiber fillers:
      1. String or cord.

2. Fabric cuttings or shreds.
3. Coarse wood fibers.

These coarser fibers are used to improve the toughness or impact resistance of the finished product as compared with the fillers listed under I*A*. However, these fillers are of higher initial cost, and they also increase the labor both in molding and finishing.

II. Inorganic (mineral):

A. Powdered or short fiber fillers.

1. Asbestos.
2. Slate.
3. Soapstone.
4. Mica.
5. Silica.

The use of these mineral fillers results in somewhat brittle products. The cost is low and molding property is good.

B. Longer fiber fillers.

The longer fiber asbestos adds to the impact resistance as compared with II*A*. It increases the compounding cost in molding and finishing.

High percentages of mineral fillers are incorporated for heat and moisture resistance or for special characteristics such as abrasion resistance.

The mineral fillers tend to increase mold wear and to make drilling as well as machine finishing difficult owing to increase in tool wear.

Laminated Plastics.—As has been suggested before, there are three chief methods by which articles are fabricated from resins: cast, molded, and laminated. Most plastics, particularly the thermoplastic, can be cast without any fillers, and can also be extruded and rolled into sheets, rods, and tubes. When plastics are mixed (often in powdered form) with finely divided fillers, such as wood flour, cotton flock, mica, or silica, and then molded under heat and pressure, the more or less homogeneous composition is termed a "molded" plastic. The properties are not different in different planes or directions in the material. Laminated plastics, by contrast, involve a treatment of sheet fillers with resin and a subsequent heating and pressing. The product of this process is usually, but not always, a flat sheet or plate; and obviously the physical structure and properties are not the same in the plane of the sheet and perpendicular to the sheet. By the use of molds and a careful shaping of the pieces of filler in successive layers, complex shapes with laminated structure can be formed. Boxes can be made in this way, as for instru-

ment cases. Angles and channels are common shapes of laminated plastics. Rods are formed by stacking filler pieces of varying width corresponding to the parallel chords of a circle.

The fillers may be woven fabrics, fibrous sheet materials, asbestos (woven or sheet), glass fiber, or wood veneer. Among the fabrics, cotton cloth is the most used material, from fine-weave thin cambric to coarse-weave 12-oz. duck. Mechanical strength is dependent on the grouping of threads in the cloth, the direction and hardness of twist, relation of warp threads to filler threads, and many other factors. The selection or often the *design* of cloth for laminated plastic use has been the subject of long engineering study. In general, cloth fillers do not offer as high electrical properties as paper and are used primarily where mechanically strong or tough insulation is essential.

Papers as fillers generally make better electrical grades of laminated plastics, but they have the disadvantage of being somewhat more brittle, weaker, and less easily machined. The cost may be lower than for cloth. Wood-pulp papers, cotton papers, mixtures of the two, hemp paper, and asbestos paper are in common use.

Glass fiber is a relatively new filler, sometimes useful to give a heat-resisting sheet; but the advantage of using glass is nullified unless the resin chosen will also withstand heat. An exception to this is the use of glass and a selected resin to give desired resistances to certain chemicals.

Asbestos cloth produces a tough and heat-resistant laminated sheet, of rather high cost. Asbestos and glass fiber may be considered substantially competitive and interchangeable materials, with certain slight advantages in favor of each.

Very tough and strong plates or "planks" can be made with resin-treated wood veneers. Poplar is a preferred wood for this purpose. Lift rods for circuit breakers where shock strength is vital is a typical application.

Resin treatment of fillers is usually accomplished by dipping in resin solutions (resin varnish) and drying without polymerizing. Many types of paper and cloth that can be obtained in large rolls are run through a continuous process and rerolled at the exit of the treating machine. Sheets or special shapes are then cut from this prepared material, stacked, and pressed hot until cured. With thick plates, this operation may take an hour or

more. The surface finish obtained is a direct copy of the pressing platen, which may be highly polished, satin-finished, or sanded.

Since there are many requirements to be met in the selection of laminated plastics and not all properties can be obtained at the same time, a number of standard grades have been recognized by the National Electrical Manufacturers Association and classified, listing the average properties to be expected. These grades

TABLE VIII.—LAMINATED PHENOLIC PLASTICS, N.E.M.A. CLASSIFICATION
(See Appendix A for properties)

Class	Description
X	Paper base in which mechanical properties are of primary importance. Not recommended for electrical applications where humidity is 30% or over
P	Paper base in which punching properties are of primary importance. Electrical and mechanical properties generally lower than class XX
XX	Paper base for general electrical applications. Grades suitable for electrical applications in both dry and fairly humid conditions of approximately 50% humidity, excepting higher voltages or low power factor at higher frequency
XXX	Paper base in which electrical properties are of primary importance, particularly for humidity up to 60%, and suitable for higher voltages or for power factor of approximately 0.04 and below at a frequency of 10^6 cycles
C	Heavy-weave fabric in which mechanical properties are of primary importance. Not recommended for electrical applications except for low voltages, low-frequency work under dry conditions of approximately 30% humidity
CE	Heavy-weave fabric base in which both electrical and mechanical properties are of importance. Not quite so strong or tough as class C
L	Fine-weave fabric base in which mechanical properties are of primary importance. Not recommended for electrical applications except for low voltages, low-frequency work under dry conditions of approximately 30% humidity. The properties are approximately the same as those of class C
LE	Fine-weave fabric base in which both electrical and mechanical properties are of importance. It has some improved properties over class L
AA	Asbestos fabric base for higher temperatures up to 125°C. for a short time of 1 hr. or less
D	Material with decorative surface used where appearance of the surface is of primary importance. Properties approximately the same as those of class X
S	Wood-base grade for special electrical applications.

may be obtained from several manufacturers, and in addition special grades for unusual conditions may be featured by each maker. The standard list is shown in Table VIII.

Synthetic Resins.—A catalogue of resins purporting to be complete today would be out of date tomorrow. There are, however, a limited number of types used in quantities large enough to warrant listing here.

PHENOLIC.—The prototype and best known is phenolic, the resin first developed by Dr. Bakeland; hence the familiar name Bakelite. Phenol, a white crystalline solid, also known as carbolic acid, is derived as a by-product of coke ovens. Formaldehyde is a gas obtained from partial oxidation of ethyl or methyl alcohol and usually exists as a water solution. Phenol and formaldehyde react under certain conditions to form water and a resin. Initially the resin is softened by heat and is soluble in alcohol, but continued heating makes it finally infusible and insoluble. This resin is used in various forms: as a cast transparent resin, in molding powders, in laminated sheets and tubes, in varnish, and in quick-drying finishes. The fillers in molding powders may be wood flour, cotton flock, asbestos, mica, or glass fiber. In laminated form the filler is paper, cotton cloth, or asbestos cloth. Appropriate varieties of phenolic resins have excellent mechanical, electrical, and chemical properties for most applications. This type of resin is probably the most widely used. Resistance to the electric spark is not good. Chemical resistance is quite satisfactory.

In recent years, cresylic acid, obtained from coal tar, is usually employed instead of phenol. A substitute for formaldehyde is found in furfural. This is a by-product of plant waste, particularly oat hulls, corncobs, and peanut shells, obtained by decomposition and extraction. Furfural acts to give the resin a sharp polymerization point at 330°F. Up to that temperature, plasticity is preserved, an advantage in molding. Molded pieces are rigid and not rubbery when taken from the mold.

UREA FORMALDEHYDE (or urea furfural) is also a thermo-setting resin and is formed by the reaction of two substances. Urea is produced by two commercial methods: (1) acid hydrolysis of cyanamide made from calcium carbide; or (2) heating of ammonium carbamate, formed from ammonia and carbon dioxide at high temperature and pressure. The resin is water-white and

is therefore useful in producing light-colored moldings. Uncured resin is a siruplike liquid that is miscible with water. This may be an advantage or a disadvantage, depending on the character of fillers to be impregnated. Paper to be coated must have high wet strength. On the other hand, some water-soluble dyes can be used easily with urea resins.

Molded parts are quite odorless and tasteless but have poor resistance to heat above 100°C. Immersed in water, they absorb moisture and swell. One valuable property is the resistance to electric sparks. No conducting track is formed on the surface until combustion temperature is reached. This is in contrast to the well-known defect of phenolic resins in this respect.

Urea resins are more alkali resistant than are phenolic resins, but they are less acid resistant.

RESORCINOL FORMALDEHYDE is quite similar to phenol formaldehyde in reaction and resin properties, the main difference being its high speed of setting. Resorcinol is a colorless, odorless crystalline material readily soluble in water. It is produced from benzene by replacing two of its hydrogen atoms with the hydroxyl OH. Its more common uses are in dyes and antiseptics. Resocinol resins are not so common for insulation as phenolics are.

VINYL RESINS are true thermoplastics, with no chemical reaction involved in molding. There are several members of this group, all being clear, odorless, tasteless, nontoxic, and slow-burning. They also possess heat and light stability and excellent resistance to chemicals and solvents. Of particular interest electrically are the series V and series X resins.

The series V resins are copolymers of vinyl acetate and vinyl chloride. The origin of vinyl acetate is acetylene and acetic acid in the presence of a mercury salt. The copolymer resins have low moisture absorption and low cold flow, do not warp or shrink, and do not deteriorate with age.

The series X resins which are products of aldehyde reaction are more heat and light resistant but less resistant to chemicals.

Vinyl resins are relatively new in the electrical field. Stability and good electrical properties will tend to extend their use where a thermoplastic is desired.

CASEIN is made from cow's milk and has been used as a plastic since 1904. Raw casein is ground and fed to extruding machines

under heat and pressure. Rods, tubes, and sheets are formed from the extruded material, and these must be cured by a solution of formaldehyde. This hardening may take 6 weeks to 6 months. The products are then dried and straightened. Forming of articles is by machining or punching operations. Casein is not really a moldable material. Although not widely used as an electrical insulator, it is used in making many small parts that are adaptable to automatic screw-machine methods.

ACRYLIC RESINS come from the polymerization of monomeric derivatives of acrylic and alpha-methyl acrylic acids. They range from soft to hard solids, all thermoplastic. The outstanding feature is transparency and stability to light, permitting them to be used as nonbreakable substitutes for glass. Discoloration does not take place with age. Electrically, acrylic resins are noted for low power factor and high dielectric strength. The chemical stability is remarkable. Acrylates are unaffected by water, 50 per cent sodium hydroxide, 50 per cent sulphuric acid, all concentrations of hydrochloric acid, salt solutions, oils, alcohols, ethers, and carbon tetrachloride.

One specific resin in this class is methyl methacrylate. It may be obtained as a cast resin or in a molding powder, fabricated in the same manner as cellulose acetate.

STYRENE is a colorless liquid that can be changed to polystyrene, a solid resin, by heating. Polystyrene is an old synthetic resin, but its use was delayed by lack of suitable methods of manufacture. The source is ethyl benzene, from which two hydrogen atoms are removed. Ethyl benzene in turn comes from ethylene gas combined with benzol.

Polystyrene is a thermoplastic, softens at 90°C., and is quite inert to chemicals. It is especially noted for its insulating characteristics, particularly for high frequency. For radio parts, its extremely low power factor, practically negligible compared with that of the usual plastics, is a valuable feature. In this, it is the equal of fused silica. It is unaffected by water, alcohol, acetic acid, and sulphuric acid but is damaged by nitric acid and is soluble in most lacquer and varnish solvents. Dielectric strength as high as 1,500 volts per mil has been noted.

ALKYD RESINS (glycero-phthalates) is the name given to a group of resins varying in consistency from viscous liquids to brittle solids. They are compounds formed by condensation of

glycerin or other polyhydric alcohols, such as ethylene glycol, and the anhydride of a dibasic acid, such as phthalic, succinic, or maleic acids. Glycerin was formerly obtained only from animal fats, but a considerable amount is now synthesized from propane (constituent of natural gas). Phthalic anhydride, in the form of beautiful, glistening white, needlelike crystals, is made by catalytic oxidation of naphthalene (the common mothball material). Of interest in the electrical industries are the chemical stability, particularly toward alkalies, and the resistance to "tracking" from sparks on the surface. Varnishes made from such resins have excellent life and durability under adverse atmospheric conditions.

MALEIC and MALIC RESINS are new and may be useful as insulating materials but have not yet been used to any extent. They are related closely to alkyd resins and probably will be chiefly of value as modifiers to obtain specific physical properties.

RUBBER.—Molded hard rubber is made by forming plastic rubber, fillers, and sulphur in molds and vulcanizing. Such products have, as among common materials, the highest resistance and dielectric strength. The faults of hard rubber are its warpage, its brittleness with age and oxidation from corona, and its poor oil resistance. The color changes from black to brown on exposure to light.

Two general classes of synthetic rubber for molding purposes are in use. The first is an ethylene polysulphide polymer derived from natural gas. Its chief virtue is resistance to action of oils and petroleum solvents. Molding powders fully compounded are obtainable for molding to shape under heat and pressure. The second type is the isoprene derivatives obtained from acetylene, which are also oil resistant, perhaps to a less extent, and may be obtained in forms for plastic molding. For electrical uses the isoprene types are preferred to the ethylene polysulphide type, for the latter is corrosive to copper. More data and properties will be found under Lastics.

Cellulose Compounds (Thermoplastics).—CELLULOSE ACETATE is a widely used member of the large family of cellulose esters. It is manufactured from cotton linters (a nearly pure form of cellulose) esterified by acetic anhydride and acetic acid to a consistency resembling flakes of snow. It is a thermoplastic material, with flammability equal to that of heavy paper or wood.

It does not yellow with age so readily as cellulose nitrate. For molding, it must be plasticized to give flow properties. Being remoldable, cellulose acetate is not resistant to heat. Molding may be carried out from blanks punched from sheets or from rods, chips, powder, or granules. The dielectric strength is high, making it adaptable to switches, telephone and radio parts, dials, and instrument parts.

ETHYL CELLULOSE is a relatively new cellulose resin that is superior with respect to chemical attack and dielectric properties. The resin is so far chiefly useful in insulating finishes (varnishes and lacquers), but it is made also into molded parts and into sheets. It is produced through the reaction of ethyl chloride on alkali cellulose. Features of this plastic are its lack of brittleness at low temperatures, resistance to all alkalies, low density, and absence of hydrolysis (which is common to cellulose esters). It is miscible with many plasticizers and other resins and waxes. Moisture absorption is exceptionally low.

NITROCELLULOSE is perhaps the earliest cellulose plastic, being closely related to guncotton, except that its nitrogen content is lower. Cotton linters are treated with inorganic acids (in contrast to the acetate), *viz.*, nitric and sulphuric acids. A useful plastic is developed by plasticizing with camphor. Solution is helped also by alcohol. A common name for these plastics is pyroxylin, which is available in rods, sheets, and tubes. After forming, these products have to be cured to remove volatile solvents. Pyroxylin is nonexplosive but burns very readily. Electrical properties are good, but both acetate and ethyl cellulose are preferred for insulation. The dielectric constant is particularly high (7.0), but the power factor is poor (high).

CELLULOSE ACETOBUTYRATE is another new plastic of the cellulose ester family, derived from an entirely different ester from cellulose acetate. It has the advantages of both the familiar cellulose nitrate and the acetate but eliminates many of their faults. It can be molded with less pressure but does not flow so readily below molding temperature. Consequently, it resists distortion below softening temperatures. Moisture absorption is low.

Cold-molded Plastics.—For the most part, cold-molded products are made of inorganic materials, usually both the filler and the binder. Being of such origin, they possess a stability

and life, particularly at temperatures in the range from 100 to 300°C, that organics will not produce. They are not high-quality insulation in respect to dielectric strength or moisture resistance and therefore are not depended upon for high-voltage service. Such products, however, are satisfactory for arc chutes, reactor cleats, resistor spacers, and other locations where resistance to arcs or heat is required along with fair mechanical strength and rigidity. Perhaps the commonest cold-molding mix is Portland cement and a filler, such as asbestos fiber or silica. Calcium silicate may take the place of Portland cement. Occasionally, sodium silicate might be used, but it is too hygroscopic to be generally suitable.

An improvement in moisture resistance is often obtained by impregnation with resins or asphalt. Such a combination renders the molding no longer inorganic, and the maximum permissible temperature is accordingly reduced. Mechanical rigidity is, of course, still maintained, and this may be the main objective.

SOLIDS

MINERALS

Quartz is a crystalline form of silica, found commonly in igneous rock. It is rarely pure or usable as found. Fused quartz may be cast or molded to simple shapes such as rods, blocks, or tubes. Because of the method of fabrication (in a very high temperature furnace), the cost is very high. The material has excellent electrical properties, particularly low dielectric loss. A low heat-expansion coefficient gives excellent heat- and cold-shock resistance. Since the softening point is 1400°C., fused quartz is useful for insulators in electric furnaces and on temperature-measuring devices.

Ground quartz or silica is useful as a filler in molded products where acid- and temperature-resistance are desired.

Soapstone, so named because of the slippery feel of the material, is a talc of gray color that is readily machined to a desired shape. Mechanical strength is low, and water is absorbed to some extent; but soapstone will withstand heat and many chemicals. Containers for liquid rheostats are made of soapstone, and also some switch-cell barriers.

Mica is probably the most useful mineral insulating material. It would be hard to imagine electrical apparatus, particularly

rotating machines, without mica as part of the insulation. There are many varieties of mica, differing from each other in composition, color, and other properties. The chemical structure is complex, being a combination principally of silica, alumina, and potash. Some grades contain magnesia and ferric oxide. Physically the material is peculiar, of a laminar crystalline form, easily split into films about 0.001 in. thick. Micas are found in widely scattered regions, including the United States, Canada, Mexico, Korea, South Africa, Madagascar, South America, and India. For electrical uses, we need consider only two general types:

1. Muscovite, or white mica, usually obtained from India.
2. Phlogopite, or amber mica, from Madagascar.

Mica splittings are graded and priced according to size, the larger pieces bringing a higher price. Most mica used for electrical purposes is made from pieces about 5 sq. in. or smaller in area. The splittings are bonded together with an insulating adhesive, such as shellac, asphalt, copal, or synthetic resins. Sheets or plates are thus reconstructed that have more homogeneous properties than natural mica as found. The final form may be rigid plate, flexible sheet, tubing, tape, or combinations with cloth or paper to give toughness. Sheets may be built by hand, by spreading splittings on a screen or a moving belt while adhesive is dripped on the mica. Automatic mica-building machines are also in use, in which mica is fed to a hopper, picked up by a vacuum drum, and laid in a sheet and bonded together, baked, and delivered finished. For best grades of plate, some hand patching is necessary to supplement the machine operation, it being impossible to cover all points uniformly. Thin spots are revealed by light beneath the moving mica sheet, and extra pieces are placed at these spots by alert operators.

Muscovite mica is harder than phlogopite and is used for undercut commutator-segment insulation. Maximum safe temperature is 500°C. Above this the water of crystallization is released, and the mica disintegrates to powder.

Phlogopite mica is darker in color (amber to brown) and is soft. It is used for flush commutators because it will wear down with the copper. The chief use of amber mica, however, is in heating appliances, for it will stand 800°C. without disintegration.

One might logically ask why mica should be used when it has a vulnerable organic bond that will stand perhaps only 105°C.

The answer is that, once the mica is in place, it does not matter if the organic material disappears. In fact, it usually does, but other parts of the structure hold the mica in place mechanically. The bond is therefore really necessary only during the fabrication of coils or other parts (see Appendix A for properties).

The chief fabricated forms in which mica is the major ingredient are as follows:

MICA PLATE is a rigid board made in thicknesses from 0.005 to 0.050 in. Liquid or powdered shellac is used for bond, and the required amount of material is compressed and baked. To obtain uniform thickness, the formed sheet is machined (by milling or sanding) on the surface. Amber plate can be punched for cores of heating elements. White mica plate is most used for commutator segment insulation.

FLEXIBLE MICA SHEET is built of white-mica splittings and modified bonds. Hot-molding mica may be cemented with plasticized shellac or phenolic resin cement. The proper shapes are cut from cold sheet, heated to a limp condition, and then pressed and cured in steam-heated metal molds. The chief use is for V-ring insulation of commutators. A variety that is flexible when cold, made with castor oil and shellac or with alkyd resin, is used for forming around slots and coils of rotating machines.

MICA WRAPPER is a composite material, built of mica splittings and some fibrous material. A common form for coil insulation is mica (two or three layers) combined with fish paper. Kraft paper, rope paper, or other varieties may be employed, or one of the insulating fabrics. Asbestos paper and mica are sometimes combined.

MICA TAPE.—For insulation of coils of rotating machines, mica tape is widely used. It is not possible to make continuous rolls of flexible mica sheet alone that can be cut into tape widths of sufficient strength for wrapping coils. To keep the amount of organic material to a minimum, a strong thin paper (mulberry fiber, known as "Jap paper") or thin cambric, not over 0.002 in. thick, may be used for a backing on which to build the flexible mica.

Marble has practically ceased to be the important insulating material for high-quality switchboards that it once was. There are still in existence many very beautiful generating-plant switch

panels, for which occasional replacements or additions are made. Good grades of marble, without metallic veins, are high in dielectric strength, although somewhat weak mechanically. Marble is a form of limestone, white in the pure state or streaked with many colors if containing metal oxide impurities. Whenever insulating panels are now used, engineers prefer composite materials, such as "ebony asbestos," which are lighter, easier to machine, and uniform in properties. The dielectric strength of blue marble in 1-in. thickness is not over 100 volts per mil.

Slate has suffered the same fate as marble. Slate panels for new installations are becoming uncommon. Small switch bases are still used, however. Two grades of slate were once used in great quantities: black, or Pennsylvania, slate; and purple, or Monson (Vermont), slate. Purple slate is much the better quality, being freer from metallic inclusions, but even then has only about 20 volts per mil breakdown strength. Its fireproof properties and mechanical strength are in its favor.

Slate is a peculiar material of marine origin, laid down in extensive beds. Electrical slate is closely related to mica and quartz but contains more than 12 mineral constituents in addition. When newly quarried, it can be split along the cleavage planes caused by prehistoric earth pressures but is difficult to split after drying and seasoning. It can be sawed, machined, and drilled with suitable tools. Cured and dried slate does not reabsorb moisture readily.

The following properties are typical of switchboard slate:

Crushing strength	15,000 to 30,000 lb. per sq. in.
Shearing strength	2,000 lb. per sq in.
Density	2.8
Insulation resistance	1 megohm per inch cube

Loss (mostly conduction loss) at 25 cycles, 3,000 volts, for acceptable slate should not exceed 20 watts per inch cube.

The energy dissipated under test varies approximately as the cube of the voltage. Consequently, slate is unsuitable for voltages above 600.

The decline in use of marble and slate has been principally due to the use of "dead-front" boards with steel panels and all live mechanism concealed or mounted on the rear with porcelain or other insulating supports.

Asbestos has been and still is a most versatile and useful insulating material, chiefly because it is fibrous (even though

a rock), can be used at high temperatures (800°F.), and is unaffected by oils, acids, and alkalies. Asbestos is a fiber crystalline mineral, in which the ultimate filaments are supposed to be chains of single molecules. Fibers are smooth and shiny and slide on each other, so that the strength in tension is not high, being about the same as that of silk. The composition includes magnesia, alumina, silica, lime, water, and usually oxides of iron. Many types of asbestos are found in several parts of the world. Only a few are sufficiently pure for electrical purposes. Chrysotile asbestos, the most useful type, is found in Africa, Canada, Russia, and the United States (Arizona). As mined, the color may be green, yellow, or blue; but when the fibers are separated, the color is usually white.

Asbestos for electrical purposes appears in several forms, as follows:

Cloth and tape, woven from asbestos fiber and cotton threads (not over 20 per cent cotton).

Paper made from asbestos-fiber pulp and white-paper pulp in sheets or rolls.

Board formed with Portland cement as a binder.

Twine—roving incorporating some cotton yarn.

Felt, applied as wire covering.

It is also molded with synthetic resins into laminated plate.

The cloth, tape, and twine are used in insulating coils of rotating machines. The paper is cemented to edge-wound field-coil strap for insulation of turns and is also used for coil-layer insulation. The board is used for panels and barriers. A molded composition using asbestos fiber, and mostly inorganic binders, is useful for arc chutes.

Asbestos, untreated, does not possess high insulating properties, because of the presence of impurities and the susceptibility to moisture absorption. Mica has a dielectric strength 10,000 times as high. In spite of these facts, asbestos is still essential. Even in the face of its newest competitor, fiber glass, asbestos shows no signs of decline.

Alsifilm is a new product developed by the Research Corporation from a colloidal-clay product known as bentonite. It has some promise as an inorganic insulating film that may be built in layers or possibly as a binder for high-temperature insulation, as for building mica plate. Its chemical and electrical proper-

ties seem good, but its life and mechanical strength have yet to be demonstrated in service. Engineers have long sought an inorganic bond, or cementing material that might also be used in films.

CERAMICS

Glass is a class name applied to amorphous solids in which silica is a major ingredient. Ordinary glasses range from 50 to 80 per cent silica; flint optical glass may be as low as 30 per cent silica; and the new reformed glass (Corning), in which the alkali constituents are dissolved out, approaches pure silica (93 per cent). The material is homogeneous and is considered a supercooled liquid having some of the characteristics of an electrolyte (see Lamps, Chap. XV). Besides silica, the ingredients of glass usually include an alkali (sodium or potassium carbonate) and lime or lead compounds. In the final fused state, glass is a mixture of silicates. Heat-resisting glass of the Pyrex type is generally known as borosilicate glass and is compounded to produce low coefficients of expansion and toughness not found in ordinary glass. Various Pyrex formulas are manufactured from the following principal constituents: silica, boric oxide, sodium oxide, alumina.

Mechanically, glass in the blown, pressed, or cast forms is weak in tension (2,000 to 12,000 lb. per sq. in.), good in compression (20,000 to 50,000 lb. per sq. in.), and brittle, although some grades are tougher than others (but not so tough as porcelain). As might be inferred, the coefficient of thermal expansion depends on the composition. For common types the values are in the range 8×10^{-6} to 13×10^{-6}, but the heat-resisting borosilicates exhibit coefficients of 3×10^{-6}.

Glasses resist most acids and alkalies (except hydrofluoric acid) but are slightly soluble in water, Soda glass, in particular, in shapes having large surface area, when boiled in water will dissolve sufficiently to give an alkaline liquid readily shown by the phenolphthalein test. For this reason, glass fiber is made of glasses that are relatively insoluble.

Electrically, glass is an excellent insulator. Its resistivity at room temperature is 10^{11} to 10^{15} ohm-cm., but this decreases rapidly with increase in temperature. In the molten state, the

resistivity may be as low as 0.1 ohm-cm. The dielectric strength is comparable with, although lower than, that of mica. Most glasses have low power factor and dielectric loss, but fused silica is superior. The power factor of glass may be 0.5 per cent at room temperature, and that of fused silica 0.1 per cent. Loss increases rapidly with temperature, particularly above 150°C.

As an insulator, glass is used in vacuum tubes, lamps, and vapor tubes, as vacuum-tight insulating seals between metals, as transmission-line insulators (both pin and suspension types) in lighting-circuit fuses, and as containers for liquid-immersed high-voltage fuses. Molded glass is perhaps the first insulating plastic historically. Like most resin plastics, glass will mold around metal inserts if the thermal expansivity coefficients are properly matched.

Porcelain.—Almost innumerable combinations of ceramic ingredients, commonly called "porcelain," are made, and a concise definition or classification is difficult. Considered as a general type of electrical insulating material, porcelainlike products can be divided into three distinguishable groups. The first may be termed "high-tension" porcelain, because of its development for transmission-line insulators. The second is "refractory" porcelain, which has some resemblance to true refractories such as are used for furnace linings. A third is a miscellaneous group, the chief member of which is "low-loss" porcelain (commonly identified as steatite), which is designed especially for high-frequency applications where low dielectric losses are essential. If the ingredients and accompanying properties of these three were to be represented as points located equidistant on the circumference of a circle, we might conceive of points within the circle as representing intermediate products partaking in composition and characteristics of all three in proportion to the relative distance to each of the three circumferential base points. If we were to place on such a chart all the useful existing varieties of ceramic products, we should find the circle well filled.

The primary ingredients or raw materials characteristic of the three elemental or unblended groups are as follows:

1. High-tension porcelain: clay, flint, and feldspar.
2. Refractories: aluminum silicate, or silicon dioxide, or spennel, or alumina, or zircon, or magnesia.
3. Steatite: magnesium silicate.

In the case of refractory porcelain, often called "heater-plate body," the straight refractory materials usually found in refractory brick are not often used alone, but one or more of the group are compounded with materials from the other two groups. The reason for moving away from the purely refractory types in the direction of high-tension and low-loss porcelains is to make a gain in: (1) dielectric strength; (2) mechanical strength; (3) ease of manufacture; and (4) imperviousness, without sacrificing seriously in resistance to heat.

Heater Plate.—This ceramic product resembles high-tension porcelain, particularly dry-process porcelain, in the way it is manufactured. It is used for electric-range bricks, furnace hanger blocks, heater bushings and eyelets, supports for ribbon resistors, terminals for flatirons, and many other parts. The composition is usually one of two kinds. One common variety contains clay, feldspar, talc, alumina, and/or flint. Another formula lists clay, feldspar, zircon, and fluxes. There are two ways to obtain good resistance to thermal shock. One is to design for low thermal coefficient of expansion. The other is to provide high thermal diffusivity quickly to equalize differences in temperature. Talc (magnesium silicate) has both good diffusivity and low thermal expansivity for a limited range of compositions.

Low-loss porcelain is usually hydrated magnesium silicate with 10 to 15 per cent clay or auxiliary fluxes. The total shrinkage from raw state to fired piece is about 7 per cent (the same as for dry-process porcelain), and dimensional tolerance is ± 1 per cent. A very critical and narrow firing-temperature range must be maintained, which contributes to the high cost of manufacture, (± 5°C. at a temperature that is dependent on the composition and is usually around 1350°C. High-tension porcelain is fired at approximately 1200°C.). The forming operations are easy because of the natural properties of talc. Imperviousness is difficult to attain because of the short firing range. If the temperature is too high, the pieces soften and slump. If the temperature is kept low enough to be safe, the body will possibly be porous. Since the losses resulting from moisture absorption must be prevented in applications such as high-frequency apparatus, impregnation and coating with waxes is usual. If desired, glazes can be applied, but often the material is used without glaze.

Low-loss porcelain is used for electronic-tube supports, bases, sockets, and high-frequency insulating parts (see Appendix A for properties).

CHARACTERISTICS OF PORCELAIN.—A summary of the advantages and disadvantages of the three types of porcelain will show their comparative merits and suggest the suitable fields of application.

1. *High-tension porcelain:*
   Advantages. Good dielectric strength, low cost, ease of manufacture, large shapes possible, impervious, good mechanical strength (11,000 lb. per sq. in. transverse).
   Disadvantages. Power factor high (0.7 per cent at 10^6 cycles), only fair heat-shock resistance, rapid decrease in electrical resistance at high temperatures.
2. *Refractory porcelain:*
   Advantages. Good resistance to deterioration by heat, good resistance to chemical attack, good strength in compression.
   Disadvantages. Fair electrical resistance at high temperatures, porous, not good in transverse strength (1,000 to 4,000 lb. per sq. in.), can be made only in simple shapes, high firing temperature.
   NOTE: This type is used for high-temperature insulation, notwithstanding its many disadvantages.
3. *Low-loss porcelain* (steatite):
   Advantages. Low power factor (0.05 to 0.5 per cent), good transverse strength (15,000 lb. per sq. in.), materials nonabrasive, easy to form, high electrical resistance at high temperatures.
   Disadvantages. Difficult to manufacture except for small parts, made impervious with difficulty, high and critical firing temperature, only fair heat-shock resistance.

MANUFACTURE OF HIGH-TENSION PORCELAIN.—The ingredients in high-tension porcelain are flint (powdered quartz), feldspar, and clay. Usually, clays of two types, known as "ball" clay and "china" clay, are blended to produce desired properties. The feldspar acts as a fluxing agent in the vitrification process, causing solution at maturing temperatures. Clays from various locations (Georgia, North and South Carolina, Tennessee, Kentucky, and England) are favored because of certain properties; but when a change is made in the source of any of the ingredients, the whole composition must be readjusted.

The various methods of fabrication fall into two general classifications known as the "dry process" and the "wet process." From a user's standpoint, dry-process products are

applied where voltage is low, moisture absorption unimportant, but accuracy of dimensions or complexity of shape essential. Snap-switch parts, sockets, and terminal blocks are satisfactory applications. Wet-process porcelain is completely vitrified and impervious, has superior electrical properties, and should be used where voltage is high, moisture is present, or radio interference must be avoided. All insulators for use on transmission lines or apparatus are made by one of the wet-process methods.

The ceramic industry has its own vocabulary which seems quite obscure to the electrical engineer. We shall explain a few of the more common terms as we proceed. The product in any stage of manufacture is known as "ware." Wet-process ware may result from several fabricating methods, such as hot-pressing, jiggering, casting, etc., which will be explained later. These operations refer chiefly to the forming of the "body" (plastic unfired porcelain) rather than its preparation, which is similar for all wet methods.

The dry ingredients are first thoroughly ground (if not already in the desired particle size) and mixed. Then water is added to disperse the clay and coat the nonplastics. This mixture becomes "slip," which is a suspension about the consistency of good cream; it is stirred well in a "blunger" (a bucket and stirring paddle), then filtered and pumped to storage tanks. From there the slip is pumped to filter presses, which extract the water so that flat circular cakes of puttylike clay are left on the cloth filters. These "filter cakes" are put through a machine like a sausage grinder ("pugmill"), which extrudes a "pug" of homogeneous body the consistency of soft putty. A homogeneous body is the distinguishing feature of wet-process ware. This is the raw material for several subsequent methods of finishing. The de-airing type of pugmill assists in ensuring homogeneity and in preventing "vugs" (sealed bubbles).

Hot-press Ware.—In hot-press ware, pieces are sliced from the continuously emerging pug and placed in plaster-of-Paris molds. In the hot-press machine a hot rotating metal form shaped like one side of the desired insulator (usually the lower side) comes down on the body and presses it into the mold and then retracts. The whole mold is then placed in a drying chamber, and in a short time the still-plastic ware can be dumped out of the plaster mold. It is then further dried under progressively controlled tempera-

ture and humidity until it is ready for the finishing operations. When this point is reached, the clay is about as hard as a cake of soap and is called "leather-hard." Finishing involves trimming, cutting reentrant curves, making grooves, and smoothing with a wet sponge. The ware is then ready for glazing and has shrunk about 5½ per cent from its original size.

Jiggered ware is formed to an insulator shape during rotation by means of a profile tool working against the body on a core. The pug of clay is formed by a template pressed against the clay, the template being a metal profile of the insulator surface. This process is used where handwork is satisfactory and the expense of tools is to be avoided. As far as working of the body is concerned, the jiggering accomplishes the same end as hot pressing.

Extruded ware for tubes, casings, etc., that have more or less uniform cross section is produced by pushing pugs through an extrusion cylinder with a shaped outlet orifice (die) with or without a core. External corrugations, grooves, etc., may be turned in a lathe on the extruded tubes when drying has proceeded to the leather-hard stage or even further. Extruded bars, turned and bored later, may be used for strain ball insulators.

Plastic-pressed Ware.—The plastic-pressing process is similar to dry pressing (in a steel mold), except that a special wet-process body is used and dense structure obtained.

Cast Ware.—Casting is used for special shapes irregular in form (not a surface of rotation) or for very large weather casings (tapered tubes). Here the liquid (slip), the high fluidity of which is obtained by chemical means, is poured into a plaster-of-Paris mold. The water is removed through absorption by the mold. Where a hollow casing or tube is desired, the plaster-of-Paris mold is filled with liquid and let stand. When sufficient wall thickness has built up by water elimination and chemical action, the liquid remaining in the center is poured out. Some operations such as trimming and undercutting of sheds are done when the ware is quite dry (known as *bone-dry*), and the material removed is in the form of dust.

Dry-process Ware.—In the dry process, the mixed ingredients have only sufficient water to permit forming under pressure in a metal mold. The body is granular and has about the consistency of wet sawdust. This mix may originate from the filter-cake stage of wet-process porcelain, dried, crushed, and remoistened,

or, more modernly, may come directly from the three dry ingredients mixed with water in a special mixing machine. After the molding, the drying, glazing, and firing follow essentially as in the wet process. The ware may be much less dense than wet-process ware. The granules never become thoroughly welded together as in wet-process porcelain, and consequently dry-process ware is not impervious.

Glazing.—We have now brought all the various parallel processes up to the glazing point. The surface glaze is applied to porcelain not to keep out moisture but to provide a surface easy to keep clean and to give desired color. Glaze is similar to body slip, being a liquid made of similar ingredients to which more flux and inorganic color pigments are added. Several colors are available, such as chocolate, mahogany, blue, gray, white, green, and black; but it is not possible to get any desired shade, because of the limited number of materials suitable for use at the high temperature at which the ware is matured. The dried ware is dipped in the glaze slip and drained. The water of the glaze slip soaks in within a few seconds, leaving the surface coated. If it is necessary to preserve any portions without glaze, these are coated with paraffin before glazing.

An important point with reference to glaze is its "fit." Its coefficient of expansion must be adjusted to that of the underlying body. A glaze that is in compression after firing is important for maximum physical properties; it will withstand vigorous hammer blows without damage, whereas if it is in tension the ware is weak and cracks with even a slight tap. This sort of failure resembles the effect of small nicks in metal parts subjected to stress. This principle has been used in the new high-strength prestressed glass in which the surface is under compression.

Firing may be done in one of three types of equipment. The oldest is a "periodic" kiln, a brick furnace shaped like a beehive, in which the ware is stacked in refractory containers ("saggers"). The opening is sealed and heat is supplied from gas or oil fuel for several days. Cooling takes place slowly, and at the end of the cycle the kiln is unsealed and unloaded. The gases of combustion pass inside the kiln.

Another furnace is known as a "muffle" kiln, either periodic or continuous; it is usually rectangular in shape with double walls.

The hot gases pass between the walls and do not enter the working chamber. It is used for large pieces where uneven direct heating would cause cracking or warping.

For economical large-scale production, the "continuous," or "tunnel," kiln is generally used. This is a long (sometimes 400 ft.) square-section tunnel with gas or oil burners spaced along the sides. Cars loaded with ware enter the kiln at one end at certain intervals of time (1 to 2 hr.) and are pushed through the kiln. Putting in a new car is accompanied by the removal of a finished car at the other end. Gas flow through the tunnel is arranged to take heat from the cooling zone to heat the entering cars.

Firing of porcelain is not simply a question of temperature but of time and temperature. It has been found most effective to use temperature indicators that take this into account. A satisfactory means is the "Seger cones," which have been in use for years. These are slender triangular pyramids about 2½ in. long that fuse at a certain definite temperatures. The cones are numbered, indicating relative melting points, a wide range being obtained by modifying the composition. #12 is a common cone for high-tension porcelain. When subjected for a sufficient time to a specific temperature, the cones soften and slump. Three cones of successive numbers (usually 20°C. apart) are placed at each desired measuring point. The low-temperature cone should melt flat, the second bend over considerably, and the highest bend a little, if correct firing has taken place.

Dimensional Limitations.—Except for dry-process pieces (which may be made with a finished tolerance of ± 1 per cent), porcelain is not a precision material, and allowances must be made for parts to be fitted to porcelain. A good figure is ± 3 per cent. In a 4-in.-diameter piece a variation of ⅛ in. in diameter may therefore be expected. Total shrinkage of wet-process porcelain is approximately 14 per cent (5.5 per cent before firing, 8.5 per cent during firing). Sagging, warping, etc., introduce variables. The total shrinkage of dry-process porcelain is in firing and is about 4 per cent. The only way to obtain closer dimensions is by tedious grinding after the piece is complete. Parallel surfaces on ends of tubes are obtained in this way. Great differences in cross section are not practicable in large pieces, for unequal rates of drying will cause cracks. A good designer will always consult the ceramic engineer of the porcelain plant before specifying

unusual or difficult shapes. Sometimes, changes in fillets or tapers not important to the final application will change the job from an impossibility or one on which the number of defective pieces will be excessive to a job that can be easily made at low cost. Low cost in porcelain usually implies small percentage of losses. These losses occur at all stages from initial forming to final firing. A good design may have 2 to 5 per cent loss (pieces damaged in process), whereas a bad design of a similar part may experience losses of 30 to 50 per cent. Sometimes the exact shape and process used have to be determined by experiment, just as for difficult metal castings.

Mycalex.—It would be correct to classify this material as an inorganic plastic, a term that also applies to many types of glass. Mycalex is composed of mica powder and lead borate or other glass bond, molded under high temperature and pressure in steel forms. The resulting product is a lead glass with mica filler. Although the raw-material cost is low, objects made of Mycalex are expensive, because of the fabricating and tool costs. Very attractive properties are, however, obtainable. Electrically, Mycalex is excellent, both in dielectric strength and in power factor. The low loss permits its use in high-frequency apparatus for mechanically strong insulating parts. It can be drilled, machined, and cut; and metal inserts can be molded in position. Some uses are brush-holder studs, radio-transmitter supports and couplings, and rectifier-anode insulators. From its composition, it is obviously suitable also for high-temperature applications (see Appendix A for properties).

Lastics

Natural.—Many natural and synthetic materials have "rubbery" characteristics. Perhaps this term is somewhat indefinite, but it usually implies a material that deforms readily under compressive, tensile, or other stresses and, when the deforming force is removed, returns to its original shape more or less quickly and completely. Both natural and synthetic lastics are mostly compounded with fillers and vulcanized.

Uncured rubber, on long exposure to light and air, loses its rubbery nature, becoming brittle, inelastic, and generally useless. Charles Goodyear discovered vulcanization, which is the combination with sulphur. The range of properties obtained in lastics,

even those based on natural rubber, is astounding. For this reason, it is useless to attempt a description of rubber as a single material. Compounds can be made like chewing gum (lastics are used as ingredients of this product) and like hard rubber; like artgum erasers and like tires.

NATURAL RUBBER starts as the white liquid exuded from several species of tropical trees and shrubs, when the bark is cut. The liquid (latex) may be coagulated by "smoking" over a fire or by acetic acid. In recent years, latex itself has proved very useful for impregnation purposes. Further, more accurate control of processing is possible by starting with latex in the manufacture of rubber products, rather than using the "smoked" raw rubber. Preserving means are used so that latex can be shipped from its source to the point of use.

Subsequent to coagulation, the rubber mass is milled and compounded with fillers, some inert and some with definite chemical reactivity, and with the sulphur required for vulcanization. Heat and pressure complete the process, the final step often requiring several hours, although complex organic accelerators are usually added to decrease the time.

Rubber is essentially resistant to most acids and alkalies but is badly softened and disintegrated by oils. Ordinarily, we think of rubber as waterproof, but many common rubber compounds are appreciably absorbent. Low-cost rubber applied to wires and cables may absorb sufficient water in moist ground or very humid buildings to permit heavy leakage currents and, eventually, circuit failures. Quality of rubber insulation must be ensured, where needed, by adequate specifications on percentage of rubber and minimum electrical properties before and after immersion in water. Ordinary rubber is oxidized by ozone much more rapidly than by air and is therefore deteriorated by corona. Special antioxidants are now used to minimize such damage, both from air and from ozone.

Probably the most important use of rubber as insulation is as a covering on conductors, both wire and cable. Its flexibility, along with desirable electrical properties, makes it a most useful covering, except where high temperatures or oil are met. Small collars and bushings of molded soft rubber fill a need for air- or watertight connections through openings in apparatus.

Gutta-percha is very similar to rubber in its origin, being obtained also as a latex from trees found in the Malay Archipelago. Cooking the latex in water forms a natural rubbery gum or resin which softens sufficiently at 65°C. to be moldable. This material is not compounded or vulcanized like rubber but is used as refined for wire covering. The limited supply of gutta-percha is largely used by a few English manufacturers but is not commercially important. Its resistance to water and oxygen are somewhat superior to that of rubber, but its possibilities, even if it were obtainable, are not nearly so varied.

Synthetic.—Although there are numerous "artificial rubbers," some of which only remotely resemble real rubber, only a few have attained commercial prominence. Of course, synthetic lastics have many uses other than as electrical insulation, but limitation to this application narrows our interest to the four types described below. Generally speaking, the electrical properties of synthetic lastics, even those compounds especially for electrical purposes, are inferior to those of good natural-rubber products. Their use is justified, in the face of higher cost, only where rubber's lack of oil and oxidation resistance rule it out.

Koroseal is described as plasticized gamma polyvinyl chloride. It is not vulcanized. An unusual range of rubbery attributes can be obtained, even at high temperature. Perhaps its most striking characteristic is the absence of odor (or color) when compared with some other synthetic rubbers. Oil resistance is good. Electrical uses include insulating casings, adhesives, and gaskets.

Thiokol, a product of natural-gas origin, is chemically ethylene polysulphide obtained as a condensation product of aliphatic dihalide and soluble polysulphide. In the unvulcanized form, it softens with heat. It can be vulcanized like rubber, with heat and metal oxides (instead of sulphur), and is then plastic and elastic, although not so definitely as rubber. Tensile strength and elongation are only fair. Where Thiokol excels is in remarkable resistance to oils, aromatic solvents, light, and ozone. The best field of application as an insulator is for the outside layer on cables and flexible cords subjected to contact with oil. Immersion in transformer oil seems unfortunately to accelerate sludging and acid formation in the oil.

Neoprene.—The raw materials involved in the manufacture of neoprene are coal, limestone, and salt, inherently plentiful and cheap. The process involved makes the final cost higher than rubber but competitive for many applications where rubber will not do. From the raw materials, acetylene is produced, and from this a chlorinated vinyl compound known as chloroprene. Four separate successive steps are required for the formation of chloroprene. Neoprene is a linear polymer of chloroprene. This product is thermoplastic when unvulcanized but is rarely used in that form. Practically all neoprene products are compounds with fillers and modifiers similar to the myriad of rubber compounds. In these forms, it is not thermoplastic. It is high in tensile strength, very resistant to oil, ozone, light, and chemicals, and is satisfactory for insulation, even in oil. Electrical applications include cables and wires, bushings, gaskets, and other uses where rubber would be unsuitable because of the effect of oil, ozone, and other agents.

The three synthetic lastics described are sometimes used with rubber, for example, as an outer coating over rubber insulation on wire, to protect the rubber from oil or ozone.

Properties of Neoprene

D.-c. volume resistivity at 25°C.	5×10^{12} ohm-cm.
Dielectric constant at 1 kc	7.5
Power factor at 1 kc	1.5 per cent
Dielectric strength at 60 cycles	800 volts per mil

Buna is closely related to neoprene, having the same origin, but is an isoprene that is not chlorinated. It was developed in Germany and for most applications is a competitor to neoprene. The electrical properties are not notably different.

Fibrous Materials

Cotton is one of the basically important insulating materials. It is one of the few currently produced raw products, being grown annually by sun energy, instead of withdrawn from the stores of irreplaceable substances created ages ago. Chemically, cotton is nearly pure cellulose and is easily adapted to spinning and other textile processes. No claim is made for high electrical properties of cotton in any form, since its dielectric strength is substantially the same as an equivalent thickness of air; but

cotton alone is rarely used. It is adaptable to many treatments, which add moisture resistance, dielectric strength, and high resistivity to the inherent valuable mechanical characteristics (see Appendix A for properties).

Cotton yarn is used for covering conductors and for insulating magnet coils (see Control Apparatus, Chap. VII, page 199). Individual threads are combined to form the yarn. Thus an 80-6 yarn means six threads of #80 cotton thread. The smaller the thread, the greater the cost. Coarse threads may be 30¢ per pound, and the very fine grades as high as $3 per pound. Cotton yarn as insulation can be considered as a mechanical spacer and a sponge to hold liquid insulating materials which later become solids. Without treatment, cotton is naturally hygroscopic and usually must be dried as part of the treating process.

Cotton cloth is chiefly used in making varnish-treated cloth and tape and for the filler in laminated plastics. Varnished cloth is made of rather fine weave (64 threads per inch). The varnish is applied by successive dipping and baking carried out as a continuous process until two to four layers of varnish are applied. Black varnishes, usually asphaltic, have good water resistance and high dielectric strength. For cable insulation, they must also possess low power factor. Inherently, they are less oil resistant than tan varnishes, which are also somewhat lower in dielectric strength. Varnished tape is manufactured in wide rolls of cloth and subsequently slit into tape widths as desired. It is possible to obtain a variety of finishes on varnished cloth by the choice of varnish. A tacky surface is used to obtain adhesion between layers, and a hard glossy surface is desired for the finish of some coils. A greasy surface (obtained by additions of paraffin to the last dip) is necessary in taping coil ends of machines to allow the turns to slide over each other. Cotton cloth woven with bias threads is preferred for tape, for the layers can be stretched around curves and corners. This implies that the varnish will stretch, also, without damage.

Cotton twine and *cord* are used for tying coils. Coil leads are often covered with *woven sleeving*, which may be without treatment or be impregnated before application. *Cotton flock* is one of the fillers employed in molded plastics to produce a tough material. Another important cotton product is *paper*, which will be discussed separately.

Fiber, sometimes called *hard* or *vulcanized fiber*, is still another essential insulating material derived from cotton. The source of material is old cotton rags from which the natural oils and resins have been worn and washed away. Rags are treated in zinc chloride or sulphuric acid to gelatinize the fibers. Layers of this fibrous mass are rolled on a drum to the desired thickness, cut off in two half cylinders, and soaked for a long time (1 week to 1 year, depending on the thickness). The soaking is progressive from strong acid solutions to pure water, which finally removes most of the traces of chemical. The sheet shrinks greatly and warps on drying and so must be pressed and calendered to form a flat sheet of uniform thickness. Rods and tubes can also be made. Continuous processes of making fiber are also to be found.

Hard fiber is usually black, gray, or red in color, not much electrical difference being present.

The great defect of hard fiber is its water absorption and consequent changes in physical dimensions and, of course, in electrical resistance. In spite of this adverse property, its other characteristics are most unusual. It is tough, easily machined or punched, unaffected by oil, and low in cost. In dry locations, its behavior is excellent. Another feature is worthy of mention. Under action of an arc, the surface gives off gas which snuffs out the arc and simultaneously cleans the fiber surface, leaving no conducting path. Fiber is therefore of great importance in fuses and arc-extinction devices.

Silk is no longer a very important insulating material. Silk-yarn-covered wire (in very small sizes) is used where space taken by cotton would be too great and where enamel does not provide enough insulation. Varnished silk cloth is likewise sometimes used for space reasons. There are not many applications, however, where cotton or rayon (if appearance is important) will not do. The decorative braid on cords was once silk but is now rayon and cotton. Silk fiber is obtained from Japan and China, spun from the cocoons of the silkworm.

Linen is also practically out of the picture, except perhaps for twine. It is manufactured from the fibers of the flax plant, mostly imported. The strength of linen at high temperatures is good, somewhat superior to that of cotton. Coil fastenings of linen cord are still used. Another limited use of linen is in con-

denser papers, some of which contain 40 per cent linen fiber with 60 per cent cotton. Cotton or wood papers have supplanted much of this form.

Hemp, another vegetable product, provides a strong fiber used in making tough, strong paper which is used treated or untreated for coil-layer insulation (see Paper). Besides its use in paper, hemp fiber is employed as a filler in insulated cable and in coils where a cushioning effect is desired as well as filling.

Paper is a broad subject, even in electrical fields. As many as 100 different kinds of paper may be used in the many electrical devices insulated with paper products. Only the most important general types can be described here. Like cotton, paper itself without treatment is not much better electrically than so much air but is a carrier for insulating impregnants. Paper is harder and cheaper than cotton fiber and has advantages in thinness and high density. The mechanical behavior in general is inferior to that of cotton textiles (see Appendix A for properties).

RAG PAPERS, made from cotton rags, are particularly tough and abrasion resistant. Some grades are used for insulation of motor slots.

FISH PAPER is another cotton paper made very much like hard fiber (by the sulphuric acid or zinc chloride treatment), except that the process is not so drastic and the paper is thinner and more flexible than most fiber. Fish paper is hard, tough, and dense, withstands sharp bending without cracking, and is not affected by oil. The dielectric strength is good when dry. Often a treatment of paraffin is given for waterproofing. It also is used for slot insulation and, in combination with mica, for coil wrappers.

ABSORBENT PAPER made from cotton rags makes good filter paper for purifying insulating oil by the filter-press method.

PRESSBOARD (sometimes called "fuller board") is widely used as transformer insulation, coil sides, washers, and coil barriers. Usually it is applied in sheets $\frac{1}{16}$ in. thick and up, although it may be obtained as thin as 0.007 in., when it is known as "express paper." Plates 1 in. or more in thickness may be made by glueing together thinner sheets. Pressboard may be a cotton product, wood pulp, or a mixture. The higher the percentage of rag stock, the less apt it is to warp and shrink and the more adaptable to forming into shapes. The advantage of pressboard,

which is tough, porous, and gray in color, is the ease of drying and subsequent oil impregnation. Insulating parts of oil-immersed apparatus can be made of the raw material and become excellent insulators when oil treated. For use in air, a varnish coating is often given.

KRAFT PAPER is a 100 per cent *sulphate* wood-pulp product, used for many purposes. It may be obtained in thicknesses of 0.0004 in. to pressboard dimensions (¼ in. or more). Kraft papers are reasonably strong, take impregnation well, and are largely used in paper-base grades of laminated plastics. Shellac-treated Kraft paper is rolled on mandrels for insulating tubes and bushings.

The 0.0004-in. Kraft tissue is useful for paper and metal-foil capacitors, having excellent dielectric strength and low power factor. It has substantially replaced paper formerly used made of linen and cotton fibers.

Sulphite paper is another variety of wood-pulp paper; it is pure, soft, and white and is adaptable for laminated plastics where a high resin content is needed. It is sometimes known as "white absorbent" or "alpha cellulose" paper.

NOTE: *Sulphate*-process paper is made by cooking the wood pulp in caustic soda and sodium sulphide, an alkali process. *Sulphite* paper comes from cooking of wood pulp in an acid solution of calcium magnesium bisulphite or in a neutral solution of sodium sulphite.

ROPE PAPER made of old rope or hemp fiber is stronger than cotton paper and is used, varnish treated, for coil insulation together with mica. Thin rope paper (0.002 in.) is obtainable in narrow ribbon form (⅛ in. wide) for insulation of wire in place of cotton yarn. It makes a tough covering, thin and readily impregnated.

JAP PAPER is a very thin tissue made of mulberry fiber and has, by reason of its long fiber, an unusual strength. It is somewhat imperfect and cannot be used in capacitors but is very useful as thin covering for wire and for a backing on which to build mica tape. Extra-thin rope paper will probably replace Jap paper to a large extent.

Glass has been drawn into fibers for many years, and fabrics of glass have been predicted and even made for a long time. Only recently, however, has glass fiber (trade name, Fiberglas) been

satisfactorily developed into an insulating material promising to take a very important place in the field. Two of the previous obstacles that have been overcome are the size of fiber and its chemical reaction. Fibers smaller than 0.0003 in. in diameter are necessary to produce flexible, abrasion-resistant yarn and to avoid the annoying skin irritation experienced with coarser fibers, which break off and sometimes enter the skin. The composition of the glass had to be so formulated that the glass would not dissolve in water or moisture, producing an alkaline reaction. The sodium content, therefore, has to be low. Glass fiber for insulation now is available in many forms: cloth (0.003 to 0.050 in.), woven tape, sleeving, yarn for wire covering, and mat used for storage-battery separators. Extensive use of glass tape has been made in motors for high-temperature service, such as cranes and railway motors.

Glass fiber is made from special grades of glass by two methods. In the "staple-fiber" process, which is the cheaper, glass balls ¾ in. in diameter are melted electrically and emerge through fine platinum nozzles. Steam blasts carry the fiber to rotating drums, which collect a mat of short fibers. This is spun into yarn and woven by usual textile methods. The "continuous-fiber" process, which produces material of superior mechanical properties, consists in drawing glass through the platinum holes and stretching the filament as it is wound on spindles, whose speed determines the thread size.

The advantages of glass fiber are that it—

Is an inorganic material, resisting deterioration and chemical action.

Has heat resistance.

Is nonhygroscopic.

Has high dielectric properties.

Is marked by absence of impurities.

Has high thermal conductivity (heat transfer is good).

Has strength at high temperature.

There are some disadvantages, which may later be eliminated. It does not withstand mechanical impact or cutting action very well. The fiber must generally be used with some organic bond or impregnant which nullifies the temperature advantage to some degree. Asbestos is by no means doomed to extinction in electric

apparatus. Both materials have a place and probably always will have (see Appendix A for properties).

Asbestos has already been mentioned under Minerals, but a word should be added about asbestos paper, a useful fibrous insulator.

For many purposes, asbestos paper made of Canadian chrysotile asbestos fiber can be used. It is made 0.005 to 1/16 in. thick and is obtainable in rolls. Wood pulp (10 to 14 per cent) and sizing are added to the asbestos fiber for mechanical strength. Flexibility is good. Asbestos is vulnerable to moisture absorption, unless thoroughly impregnated. Occasional particles of magnetic iron are found in Canadian asbestos. Careful inspection is therefore necessary.

A better grade, substantially free from iron oxide, is made from Arizona chrysotile asbestos. This is used for insulating turns of strap field coils. Another important application is the covering of wire (round and square) for motor coils. For this purpose the paper is slit into tape and applied with adhesive to the wire in a covering machine.

Asbestos is a fibrous material but is also a mineral and was described chiefly under the latter heading.

Wood.—As has been noted, wood is the source of many useful electrical papers. Also, in veneer form it was described as a filler for laminated plastics.

At one time, wood was considered the basic structural insulating material. In transformers, many parts, such as spacers, coil clamps, frames, and even terminal boards, were once made of wood. White pine was preferred, because it is free from sap streaks and is readily impregnated with oil. Insulating structures for high-voltage apparatus can be constructed of varnished wood. For strength with good electric properties, maple serves admirably. Wood is rapidly being replaced by laminated plastics in the form of plates, angles, and tubes. Another use of maple is for cleats, spacers, and tying blocks used in bracing the end windings of large machines. The lift rods of circuit breakers are frequently made of hickory, a tough, strong wood. Second-growth hickory is preferred, because it is denser and more shock resistant. One method of selecting or specifying hickory for this purpose is to place a lower limit (approximately 4 lb. per cu. ft.) on the density acceptable. This usually ensures adequate

strength. Here, also, laminated plastics have claimed part of the production. Wood strain insulators made of hickory are in common use for trolley-wire suspension. For this application the wood is oil treated and varnished. The advantages are mechanical strength and small radial dimensions (for low clearances and bridges and tunnels). Here again, however, the suspension and supports have been modified to use porcelain, so that wood is rapidly disappearing.

We have, then, wood, linen, slate, marble, soapstone, and gutta-percha, which were once essential dielectrics, now rapidly being superseded.

Cellophane is hardly a fibrous material in the usual sense but is derived from wood fiber by a chemical treatment resulting in "regenerated cellulose." The final product is transparent, strong, a good dielectric, and a very pure form of cellulose. Without treatment, it is somewhat moisture absorbent but can be waterproofed with lacquer. Obtainable in sheet, tubing, and tape, it is used for wire covering and coil insulation. Cellophane is nonabsorbent when compared with cotton yarn or tape and is therefore not suitable for impregnation.

Cellulose acetate, described before as a thermoplastic, can also be obtained in the same forms as cellophane. It is slightly superior to Cellophane for electrical purposes. Neither is particularly flammable, not any more so than paper.

Rayon is the generic name of fibers derived by chemical means from cellulose. There are four general processes, the earliest being the formation of cellulose nitrate solution, which is then extruded and reconverted to cellulose. This process is now almost obsolete. The cuprammonium process dissolves cellulose in an ammoniacal copper solution, extrudes it, and reconverts it to cellulose. The viscose process employs a mixture of alkali and carbon disulphide to produce cellulose xanthate, which is extruded and reconverted to cellulose. These processes result in a product which, like cellophane, is regenerated cellulose, *i.e.*, cotton fibers changed into solid, straight, cylindrical fibers. The fourth process employs glacial acetic acid to form cellulose acetate, which after extrusion is not converted, so that the final fiber is cellulose acetate, rather than regenerated cellulose.

Rayon is used as covering for small wires, braid on lamp cord, and tape used on coils where a smooth surface, even after impreg-

nation, is desired. Electric properties are the same as those of related cellulose products.

Nylon.—The newest fiber, first publicized for toothbrush bristles and for women's stockings, is a fiber product of the E. I. du Pont de Nemours & Company that is not related to the rayon type of fiber. Nylon (a coined name) is similar in chemical composition to natural proteins such as hair and wool but has no exact equivalent in nature. It is a material that can, like certain cellulose products, be spun as a fiber or made in other forms. The name covers a group of products, called synthetic polyamides, made from nitrogen-bearing compounds, and resulting in complex chemical structures. The fiber strength and elasticity may be of interest for electrical uses. Particularly, the high wet strength seems valuable for treating processes involving liquids. Although the electrical properties will possibly not be exceptional, the fortunate combination of mechanical properties may make the product a very useful dielectric.

CHAPTER V

INDUSTRIAL MOTORS AND GENERATORS

Although there is no sharp distinction between large motors (or generators) and small motors, we may conveniently consider machines up to 100 hp. as belonging to the sizes made in large quantities for various industrial uses. Above this rating the mechanical structure, the increase in usual supply voltage, special speed requirements, or other features may limit the amount of standardization possible, so that general descriptions become difficult. In the lower horsepower classification, however, similar methods of insulation construction are in use by many manufacturers and for many ratings of motors. In the case of direct-current machines, generators may be included, having substantially identical construction as motors of the shunt or compound types. Series motors for railway, crane, or marine applications are somewhat different but have insulating features common to other direct-current machines. Alternators of small size resemble direct-current machines, if provided with a rotating armature, except that the commutator is replaced by collector rings. Again, the armature of a rotating-field alternator is

Direct-current Motor	Alternating-current Induction Motor
1. Armature:	1. Stator:
Conductors.	Conductors.
Coils or ground insulation.	Coils.
Slot lining.	Slots.
Coil ends.	Coil ends.
2. Shunt field:	2. Rotor (wound):
Conductors.	Conductors.
Coils.	Slots.
Ground.	
3. Interpoles or series field:	3. Collector rings (wound rotors).
Conductors.	
Coils.	
Ground.	
4. Commutator segments.	4. Brush studs (wound rotor).
5. Commutator V-rings.	
6. Brush studs.	

similar to the stator of an induction motor. If, then, we describe the methods of insulating the parts of a typical direct-current motor and a typical induction motor, we have covered the major principles involved.

Our first approach is to call to mind the parts where insulation is necessary and for what purpose. In the list on page 133 alternating-current and direct-current machines are compared.

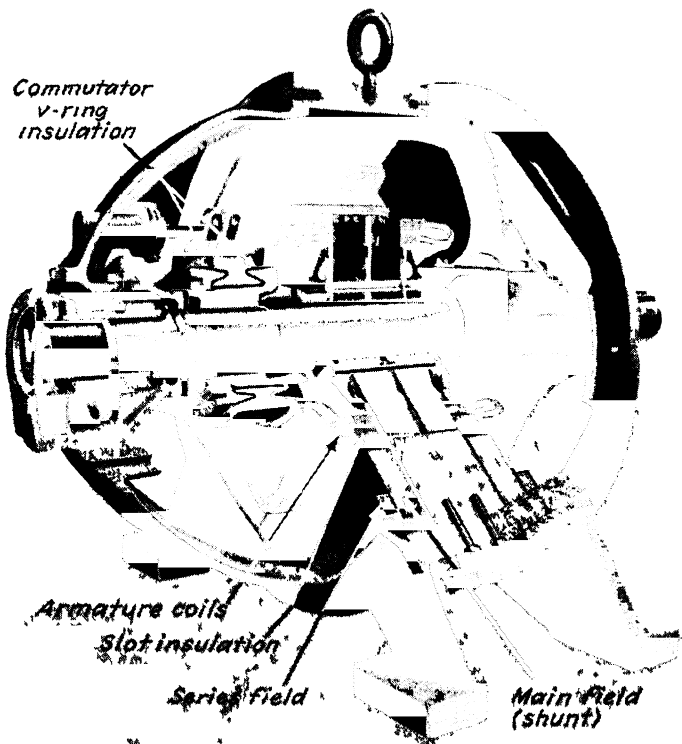


FIG. 36.—Cutaway view of direct-current motor (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The induction motor seems to be favored, in having fewer and easier parts to insulate. Perhaps this fact contributes to the preference for induction motors in spite of their lack of adjustable speed characteristics.

Direct-current Machines. ARMATURE COILS.—For small machines, round wire insulated with a double cotton covering

seems to be preferred; but when current-carrying capacity calls for more copper, square or rectangular conductors are used, again covered with two layers of cotton. Sometimes copper strap (which might be described as a slenderized rectangle) is wound bare, and sheet insulation slipped between or wrapped around the layers.

An armature coil is a relatively rigid object, even though wound of small wire. This mechanical job of making a coil a more or less solid unit is achieved by a series of operations. The wire may be wound on a wooden form to final shape and then taped or wound in an ellipse and put in a "coil puller" which pulls and

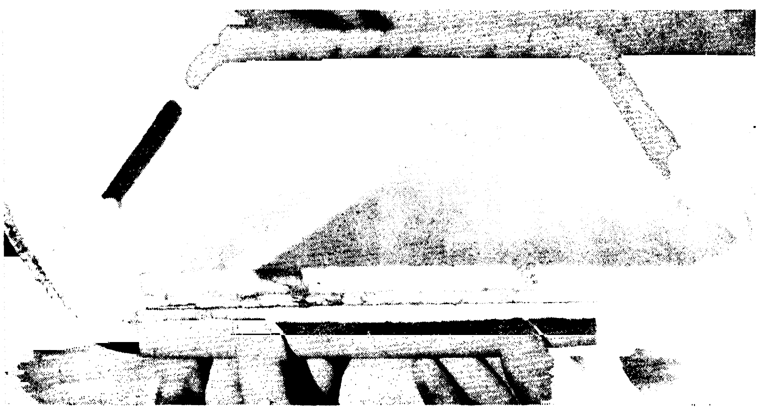


FIG. 37.—Applying mica fish-paper wrapper to slot portion of coil. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

bends the loops to proper shape. After forming the coil, the slot section is wrapped with sheet insulation (called "ground" insulation), for example, a combination of mica and fish paper (Fig. 37). Then cotton tape is applied (called "binder" insulation), lapped on the end portions, and butted in the straight portion (over the wrapper). Coils are placed in the slots of the armature, so that one coil side is in the bottom of a slot and the other coil side is in the top of a slot one pole pitch distant. Thus the coils overlap continuously, somewhat like shingles. The sides of slots in the core may be somewhat rough in spite of careful assembly and smoothing with a file. A liner ("slot cell") of strong insulating paper is therefore put in each slot before the coils are placed. Fiber wedges at the top of the slots hold the

coils in place. End windings (beyond the core) are usually held against centrifugal forces by soldered banding wire wound over a strip of tough insulating paper or cloth.

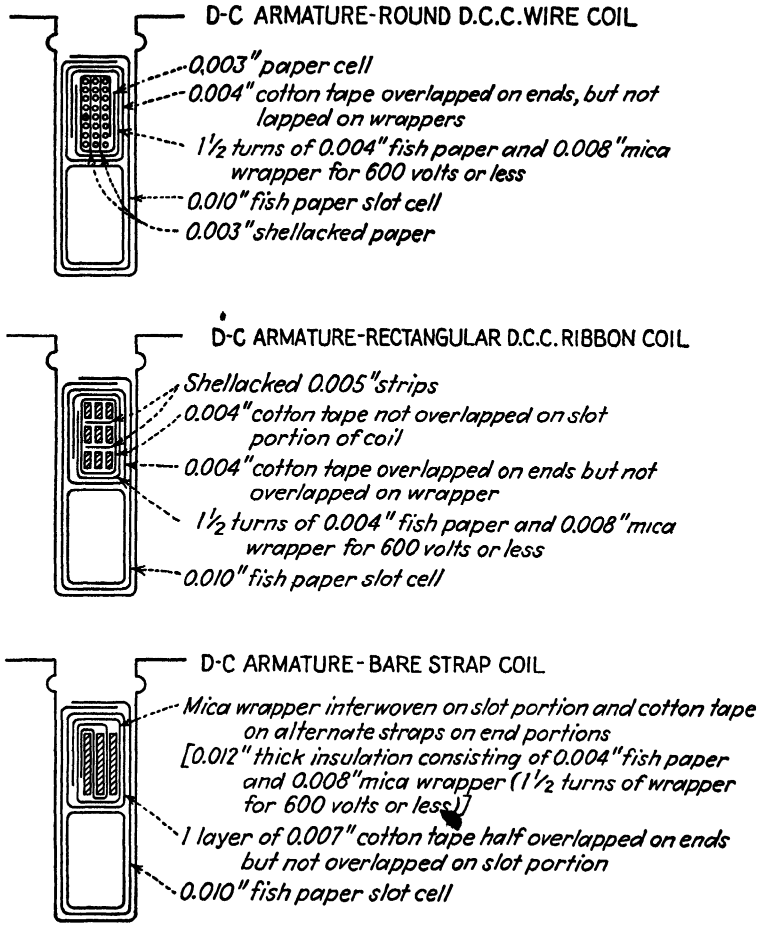


FIG. 38.—Slot insulation of direct-current motors. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

In many armatures, the coils are dipped in varnish and baked two or more times before assembling in the slots. Then the assembled armature may be dipped and baked again. The final result is then a rigid and tough protection for the windings.

The problem in armature-coil insulation is not the attainment of exceptional dielectric strength or low dielectric losses. The insulation has the combined duties of keeping the conductors spaced apart, held rigidly in place, of removing heat from conductors, and of keeping out moisture. The materials, then, when impregnated, must resist abrasion and centrifugal force and be dense enough to conduct heat away and prevent entrance of moisture, oil, dirt, and fumes. Evidence that the duty is more mechanical (spacing and holding) than electrical is the common practice of using the same insulating procedure for all circuit voltages up to 600 volts. Another requirement must be added—low space factor. Since room taken up by insulation is not productive of power (mechanical or electrical), it is in a sense waste space to be kept to a minimum. Hence, insulation is sought that is a fair insulator but is principally strong and tough and temperature resistant when thin. The substitution of paper and cellophane for cotton as wire covering in certain designs is a step in this direction. The economies of thin insulation are cumulative. Smaller slots can be used to contain the same copper, the armature can be smaller, the whole machine can be smaller for the same rating.

The composite picture of insulation of armature coils can be illustrated by the diagrams of coils in slots shown in Fig. 38.

In the case of round wire in a representative design, we thus have as a minimum between conductor and ground (iron) the following:

0.004 in.	two layers of cotton yarn
0.003 in.	layer of paper
0.012 in.	combined fish paper and mica
0.004 in.	cotton tape
0.010 in.	slot cell liner
0.033 in.	total

The dielectric strength of this amount of material may be 20,000 volts, seemingly excessive even for 600 volts. This gives point to the statement that insulation for rotating machines is built for mechanical service chiefly and that the intrinsic electrical properties are secondary.

Coil Treatments.—A variety of coil treatments may be applied, depending on service to be met and mechanical condi-

tions, such as vibration, speed, or temperature. Varnish is not the only material used for impregnating. Bakelite will make a solid, hard coil, impervious to most harmful substances; but the coils may be brittle and not suitable for resisting severe vibration. Another impregnant is gum, which may be asphaltic, fossil, or from wood pitch. Many gums are not oilproof, however, and it is difficult to make gum enter a deep coil. One problem with varnish is removing solvent. It seems futile to put solvent in varnish and then try to remove it. There has been much research to find materials that harden without air and that do not produce water or fatty acids in "setting." One improved material is "solventless varnish," which is what its name indicates. It must be applied hot. The use of a sequence of vacuum (to remove moisture and air) and then pressure helps in forcing impregnating materials into coils.

It is reasonable to inquire what impregnation is for and what may be expected of the process. Keeping in mind that coil insulation has mechanical functions that often overshadow the electrical in prominence, we find that the usual fibrous insulation (cotton tape, yarn, and various papers) is tough and strong but in an untreated condition is little better electrically than so much air space. Even this would be sufficient to meet electrical tests, provided that the fibrous insulation stayed clean and dry. Some treatment, therefore, becomes necessary, usually with a material that can be applied in liquid form. A good job of treatment involves thorough filling of the fibrous material, which, microscopically considered, means filling or at least coating each fiber. Ordinarily, such individual fibers contain moisture that resists displacement by varnish. Withdrawing the residual moisture by vacuum, driving it off by heating, or a combination of both methods forms the initial step in an impregnation process. One might reason that complete dryness should be sought; but this is an error, not for electrical reasons, but again on the mechanical score. Since tensile and abrasive strength are impaired seriously if all moisture is removed, a minimum residue is left to give "life" to the fibers. A drying and impregnating process is thus a compromise. In some cases a surface-sealing coating is sufficient, without complete saturation, particularly with impervious materials such as cellophane or other film insulation. Much of the internal cementing or bonding action of impregnating materials is sacrificed, however, with such impervious insulation.

FIELD COILS.—*Shunt fields* are commonly wound on hollow spools of insulating material (Bakelite or fiber) and then impregnated and baked, so that the coils are solid and self-supporting (Fig. 39). Another reason for the impregnation is the transfer of heat. Large field coils may be wound in separate sections fitted together concentrically with spacers between. This allows better circulation of air. The forms, or spools, are slipped over the main poles and wedged or otherwise fastened in place between

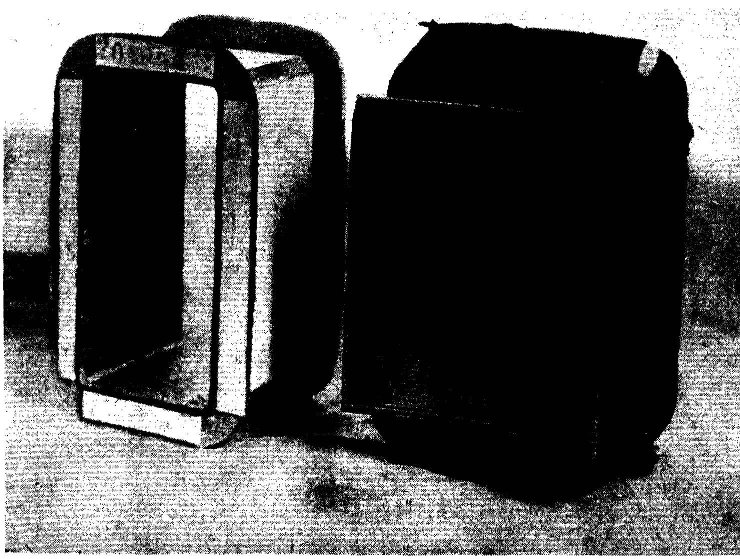


FIG. 39.—Field-coil form and assembled pole. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

the pole tips and the frame. On small machines, coils without insulating backing may be placed on the poles directly.

Series-field coils of larger cotton-covered or taped strap wire are sometimes wound on the outside of shunt coils. A preferred arrangement for ventilation and repair is provided when the series coils are separate and placed away from contact with the shunt field.

Commutating-pole, or *interpole, coils*, frequently edge-wound copper strap, require little insulation between turns, and enamel may be ample. Strips of asbestos or paper may be cemented

between turns. The insulation to ground is given by layers of paper, fiber, or tape on the pole body.

Commutator Segments.—At first glance, it may seem odd that such high-quality insulation as mica should be used for insulating the bars of direct-current commutators. (Figs. 40*a*, *b*). The voltage between bars is often only a few volts and rarely

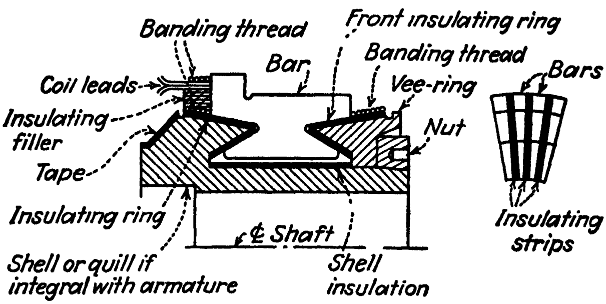


Fig. 40*a*.—Commutator section with nut fastening. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

above 20 volts; yet we find segment mica plate 0.010 to 0.040 in. thick used to separate them. The reason appears when we set down the essentials such insulation must possess. It must be temperature resistant (mechanically and electrically), moisture resistant, noncarbonizing under poor commutating conditions,

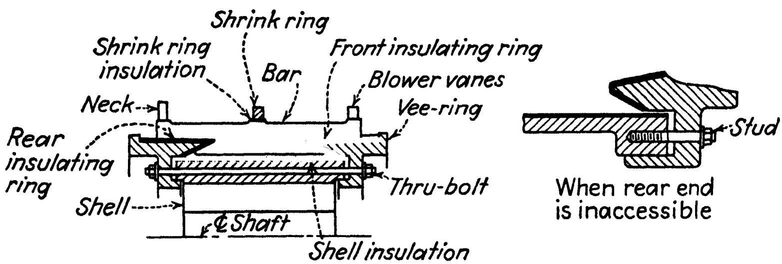


Fig. 40*b*.—Commutator section with bolt fastening. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

must have a uniform and stable degree of compression during and after assembly of the commutator, must (for certain motors) wear with the copper without ruining the carbon brushes, and must not slip out of place with repeated heating and cooling. Many substitutions have been tried and abandoned, mica still being the only successful material.

The amber type of soft mica splittings, bonded with modified shellac, is usually found in commutators where the mica is flush with the surface. The mica and copper then wear down together. There are probably more direct-current machines, however, with undercut mica; and here we may encounter either white- (hard-) mica plate or amber mica, bonded similarly. Design of the bonding material represents a real problem, and the success of the solution is measured by rigid requirements on percentage

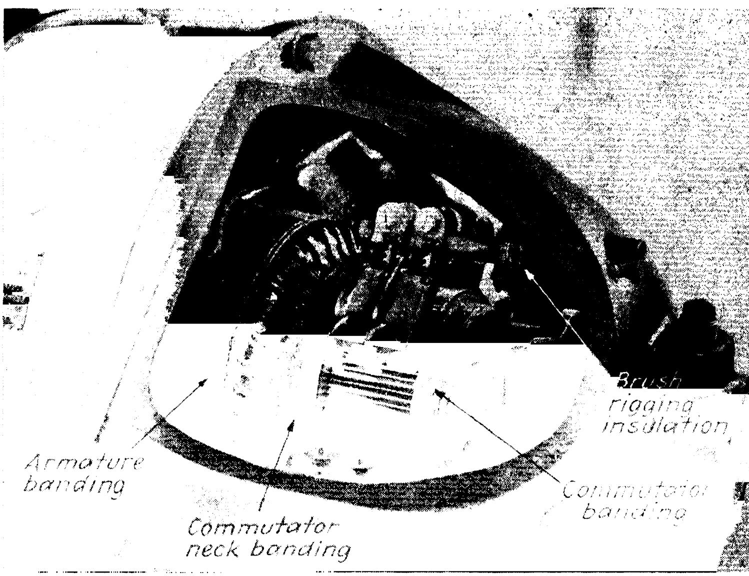


FIG. 41.—Commutator and brush details of direct-current motor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

compression under pressure (1,000 lb. or more) and on the tendency to slip or "ooze" out under heat and pressure. The preferred percentage of compression depends on the design of commutator structure, whether it is V-bound or arch-bound. The values may cover the range 2 to 7 per cent at 1,000 lb. per sq. in. pressure.

COMMUTATOR V-RINGS.—Most commutators use a form of V-ring for holding the segments tightly in a circle and to the armature spider. Since the ring parts are in contact with the spider and shaft, they must be insulated from the assembly of segments. A flexible molding mica sheet serves this purpose.

It is formed (having a flexible bond) to the required contour in a press and baked rigid. It must be hard and tough to resist the high assembly pressure and the possible cutting action of the mechanical parts.

Brush Rigging.—Simple brush holders are clamped to studs that have an insulating sleeve (fiber, Bakelite, or porcelain) or bushing. On some machines, however, there are many brushes

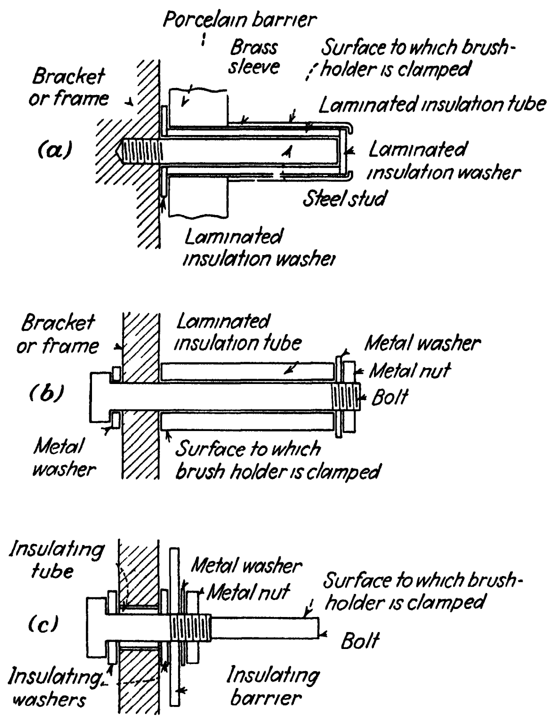


Fig. 42.—Brush-holder insulation

in a set. The bar, or arm, on which the individual brush holders are mounted must then be supported and insulated from the frame. Plates, washers, or bushings of phenolic sheet are interposed to form rigid insulating supports (Fig. 41).

Brush Holders.—The insulating mounting of brushes may take several forms. What we must have is a rigid mechanical cylinder or stud to which the assembly of brush box, support, and spring tension mechanism can be clamped. Three ways of

providing this stud are shown in Figs. 42*a*, *b*, *c*. In Fig. 42*a*, a stud (screwed into the main frame or end bracket) is surrounded by laminated phenolic insulation through a combination of washers and tube. A porcelain ring provides surface creepage, and the end of the stud is covered by a thin brass sleeve to which the brush holder is clamped. In some designs a separate ring (rather than bracket) is used to support all brush groups. By means of a through bolt (Fig. 42*c*) surrounded by laminated phenolic insulation, an insulated surface for clamping is made. Light-duty rigging can be clamped directly to an insulating sleeve slipped over a bolt.

Since brushes must slide freely in their holders, current conduction through the sides is purposely negligible. Copper-braid shunts are used for the main current path from terminal to brush body. In parallel with this path, and also in good contact with the brush, is the pressure spring, often made of spring steel which would be damaged by heating. The brush spring is frequently insulated, therefore, to keep it from carrying current which might remove the temper. This can be provided at the spring support or at the point of contact with the brush. In any case, the requirements are not severe electrically. Thin pieces of asbestos paper would be ample and would stand the local heat.

Railway Motors.—To describe every type of direct-current machine and its insulation would be a major task, for many special conditions have to be met. Our discussion should, however, describe wherein the features of railway motors and hoist motors differ from those of the industrial general-purpose motor. Insulation is required for the same parts in much the same manner, but the conditions of service are much more severe. The conductors are insulated with asbestos, either felted on the wire or wrapped with asbestos-paper tape. A recent competitor of asbestos is glass fiber which is used both as wire covering and in tape form.

Extra care is given to certain parts in the design of insulation in railway- and mine-locomotive motors, the reason being the high operating temperatures (hot spots may reach 175°C.) resulting from demands for high weight efficiency, the bad ambient conditions of dirt and moisture, the shocks and vibration inherent in such service, and finally the urge for freedom from failure in service.

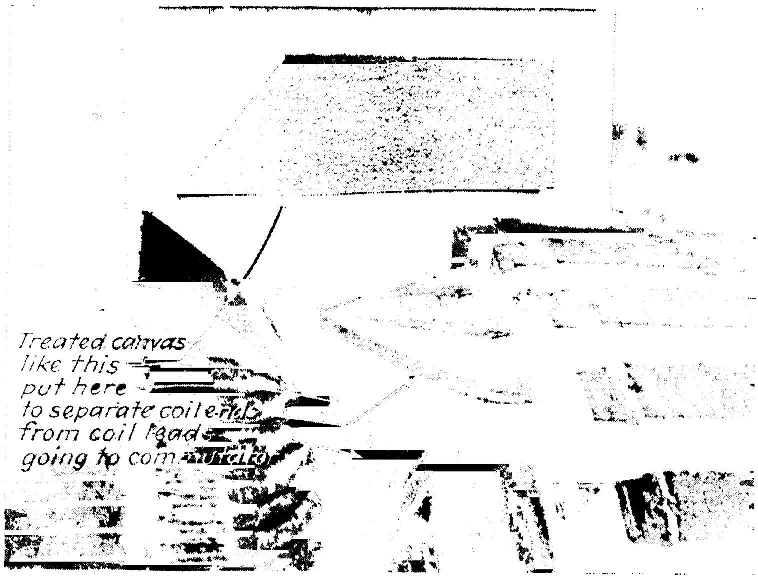


FIG 43 —Direct-current railway armature protection of coil ends (*Courtesy of Westinghouse Electric & Manufacturing Co*)

FIG. 44 —Direct-current railway armature, detail of padding of coil ends and coil leads at commutator end (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Some of the special points built into so-called "railway" insulation will be illustrated, particularly those relating to construction outside of armature slots. Other types of machines, such as induction motors of both squirrel-cage and wound-rotor types, also find use for such details of insulation, where service conditions warrant.

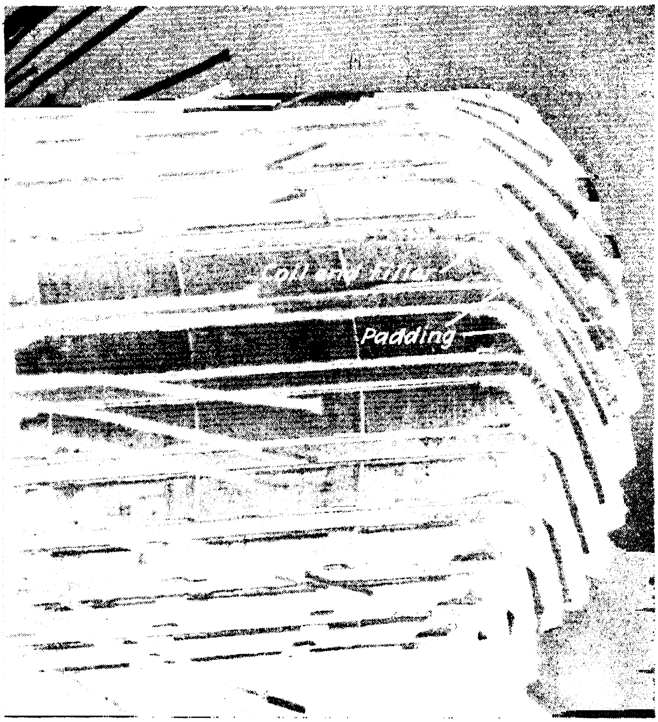


FIG. 45.—Rear end of railway armature before banding. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

In the common form of coil, one end at least usually has a "diamond point," the name given to the end-winding configuration involving a triangular outline with a loop or twist at the vertex. As the coils are nested together, the successive diamond points are in contact, and extra insulation is applied between touching coils, consisting of varnish-treated asbestos pads. These pads are folded over and trimmed to shape after all coils are in place. At the other (commutator) end of the coils, similar

pads are placed between upper and lower coil leads, and again between the leads and the coil diamond points [when both ends of the coil have the triangle and loop (Figs. 43, 44)].

To insure rigid coil ends, filler strips of fiber or treated pressboard are fitted between the straight sections of the end windings (Fig. 45). When the banding wire is later applied, the windings are compressed to form a solid ring which is wedged tight and will not collapse. This condition is known as arch-binding, a term applied also to one type of commutator construction.

Banding is applied to armatures, as required, to resist the centrifugal force tending to throw coils out of the slots (Fig. 46). On simple small armatures, only a few bands, one near either end

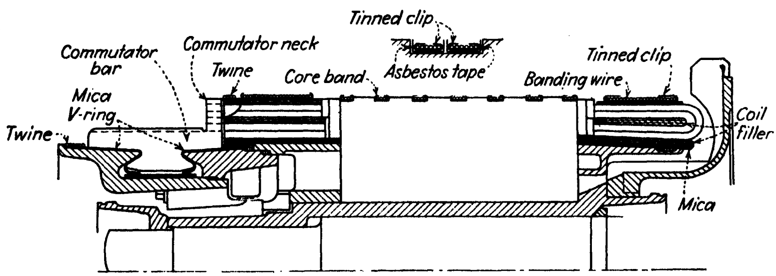


FIG. 46.—Section of direct-current railway armature. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

of the core and one in the middle, may be necessary, outside of the end-winding bands. Grooves are provided in the core for banding, so that the final surface will not project into the air gap. Often it is necessary to insulate the banding wire from the core to prevent heating from eddy currents. For this purpose a strip of asbestos tape is first laid in the groove. Over this, a strip of tinned steel is sometimes wound, and then the turns of banding wire are added under tension. The whole band is thoroughly soldered, strip and wire together. At various points around the circumference, small tinned strips, placed in the top of slots, are bend around the wire and also soldered as clips to bind the turns together. Banding is also applied over the coil ends, beyond the core, usually with more insulation under the wire.

If the filler-strip construction called arch-bound end turns is not used, a metal bracket or coil support is necessary inside the coil ends as a foundation against which to bind the turns. Otherwise, the turns would collapse.

For motors in general, we have noted that the same general plan obtains: first, conductor insulation; then coil or ground insulation; and then, usually, a binder to hold the ground insulation in place. Although many different insulating materials and products find use in motor insulation, they can be clearly classified according to the foregoing steps, the American Institute of Electrical Engineering classification of insulation known as

TABLE IX.—CLASSIFICATION OF CONDUCTOR INSULATION*

Class O	Class A	Class B
Single-cotton-covered wire Double-cotton-covered wire Silk-covered wire Paper insulated Cotton-taped conductors Silk-taped conductors Cotton sleeving	Enameled wire Single cotton and enamel Double cotton and enamel Silk and enamel Paper and enamel Cellophane and enamel Cellophane-insulated wire Treated tubing Treated tapes Treated papers Treated silk	Asbestos-insulated wire Asbestos paper Asbestos tapes Asbestos cloth Asbestos sleeving Mica tapes† Spun-glass-insulated wire Spun-glass tape

* FERRIS, R. E., and A. C. ROE, "Armature Winding and Banding Data," *Elec. Jour.*, vol. 34, p. 163, 1937; vol. 35, p. 284, 1938.

† This includes the various combinations, such as paper and mica, cellophane and mica, and cambric and mica.

TABLE X.—CLASSIFICATION OF GROUND INSULATION*

Class O	Class A	Class B
Untreated papers	Treated cloths	Mica
Fish paper	Treated cambrics	Mica and paper
Fuller board	Treated silk	Mica and cambric
Untreated cambrics	Treated papers	Mica and Cellophane
Untreated cloths	Cellophane	Asbestos and mica
Untreated silk	Micarta	Asbestos paper
Wood	Treated wood	Asbestos base and Micarta
Fiber	Molded materials	Molded material and asbestos or mica fillers, etc.

* FERRIS, R. E., and A. C. ROE, "Armature Winding and Banding Data," *Elec. Jour.*, vol. 34. p. 163, 1937; vol. 35, p. 284, 1938.

TABLE XI.—CLASSIFICATION OF BINDER MATERIALS*

Class O	Class A	Class B
Cotton tapes	Treated cotton tape†	Asbestos cloth
Silk tapes	Treated silk tape†	Asbestos tape
Cambric tapes	Treated cambric tape†	Spun-glass tape
Surgical tapes	Treated surgical tape†	
Webbing	Treated webbing tape†	
	Friction tape	
	Rubber tape	
	Treated paper tape	

* FERRIS, R. E., and A. C. ROE, "Armature Winding and Banding Data," *Elec. Jour.*, vol. 34, p. 163, 1937; vol. 35, p. 284, 1938.

† These tapes are generally applied untreated; then the finished coil is varnish-treated, changing the classification to A.

classes O, A, and B being also taken into account. The accompanying tables will summarize motor-insulating materials satisfactorily for our purposes.

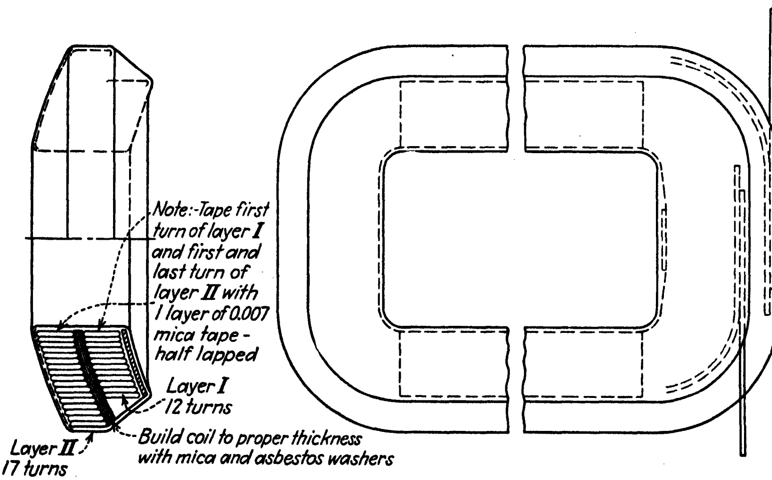


FIG. 47.—Main field coil of direct-current railway motor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

RAILWAY FIELD COILS.—Three features distinguish field coils used in transportation motors: (1) Class B insulation is demanded. (2) The conductors are large (usually strap) because the motors are series wound. (3) The space allowable is small, because of limitations of motor diameter. The coils, therefore, look a little odd in shape, as can be seen in Fig. 47.

Interpole coils are quite similar, except in dimensions, to the main field coils.

TABLE XII.—INSULATION DESIGN OF TYPICAL RAILWAY-MOTOR ARMATURE COILS

900 volts, 25 cycles	1,500 volts d.c.	3,000 volts d.c.
0.015 in. cotton tape	0.017 in. asbestos tape	0.0175 in. asbestos tape
0.020 in. fish paper and mica	0.024 in. fish paper and mica	0.048 in. fish paper and mica
0.007 in. cotton	0.007 in. cotton	0.007 in. cotton
0.008 in. mica tape	0.008 in. mica tape	0.008 in. mica tape
0.050 in. total	0.056 in. total	0.0805 in. total

Induction Motors.—There is one important difference when we compare induction-motor stators with direct-current armatures: the shape of the slot. In general, there are four main forms of slot used in modern induction motors: (1) the entirely open slot (Fig. 48*a*) with grooves for the wedges that retain the coils; (2) the partly closed slot with center opening, as shown in

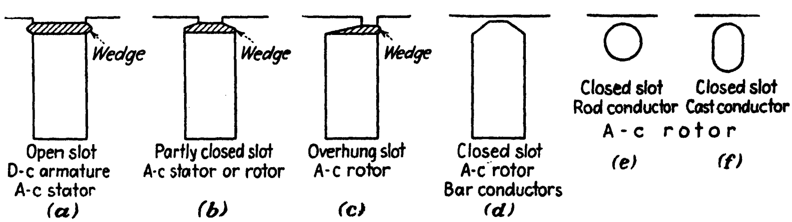


FIG. 48.—Motor slots.

Fig. 48*b*; (3) the overhung slot with side opening, as shown in Fig. 48*c*; (4) the completely closed slot (Figs. 48*d*, *e*, *f*). The open slot (Fig. 48*a*) is used on practically all stators of the larger motors. The slot in Fig. 48*b* is used on practically all motor stators from fractional horsepower up to 40 or 50 hp. and on practically all small wound rotors and large squirrel-cage rotors. The overhung slot (Fig. 48*c*) is used on large wound rotors, and its advantage lies in the mechanical security that the overhanging tooth-tips provide against the coils flying out of the slots by centrifugal force.

The closed slot has a bridge completely closing the top of the slot; but this bridge is very thin, at least at the center. This type

of slot is used on squirrel-cage rotors with aluminum die-cast windings, to facilitate the casting operation, and also with other types of squirrel-cage windings where either high impedance

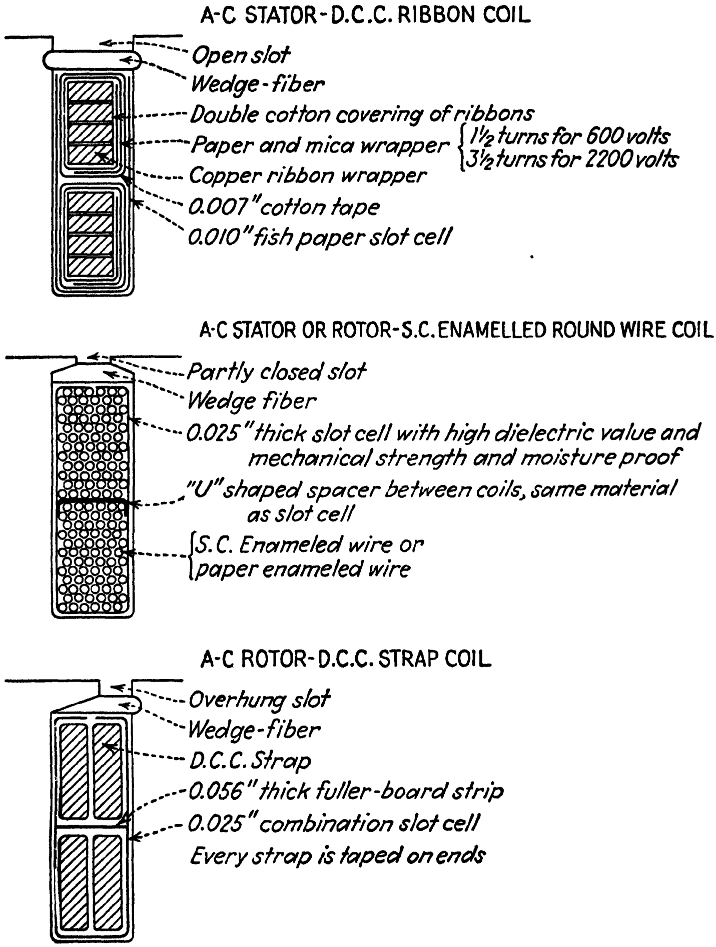


FIG. 49.—Slots and windings of induction motors. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

or quiet operation is desired. This solid bridge reduces the effect of the slot openings and the resultant pulsation of the flux as the rotor revolves.

FORMING THE COILS AND WINDINGS.—The form-wound diamond coil, as used in open-slot stators, connected in the common pole-phase method of group connection, will be described first. These coils are of the well-known form shown in Fig. 50, and the stator during winding looks like Fig. 51. Originally, such coils were wound on a wooden form which gave them at once their final form; but a later development produced the "pulled" coil in which the proper number of turns is first wound on a straight shuttle with parallel sides and which when taken off looks like a long flattened letter O. These preliminary coils are then placed in a pulling machine, which takes hold of the sides and pulls them apart and into a different plane until the shape desired for the coil is reached.

FIG. 50.—Induction motor coil before taping. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The next step in the winding is to place all these coils in the slots, one after the other, with suitable cells of fish paper or other insulation to protect them against mechanical injury from the edges and corners of the steel laminations with which the core is built up. From the figures, it will be seen that these coils go in overlapping one another and that each coil has one of its sides in the bottom of a slot and the other in the top of another slot one throw, or pitch, distant (Fig. 52). This form of winding is substantially the same in elements as for direct-current armatures, except that the slots are on the inside of a circle in induction motors and on the outside of a circle for direct-current armatures.

The major insulation on the slot portion of the coil is the wrapper, composed, for example, of 0.004 in. fish paper, three layers of mica splittings (0.007 in.), and a top layer (0.001 in.)

of Jap paper. If, as is sometimes the case in conservative calculations, the other insulation (cotton yarn, binder tape, and cell liner) is considered only as mechanical protection of negligible dielectric strength, we find that the dielectric stress is still quite low. One layer of wrapper used for 600 volts is stressed only

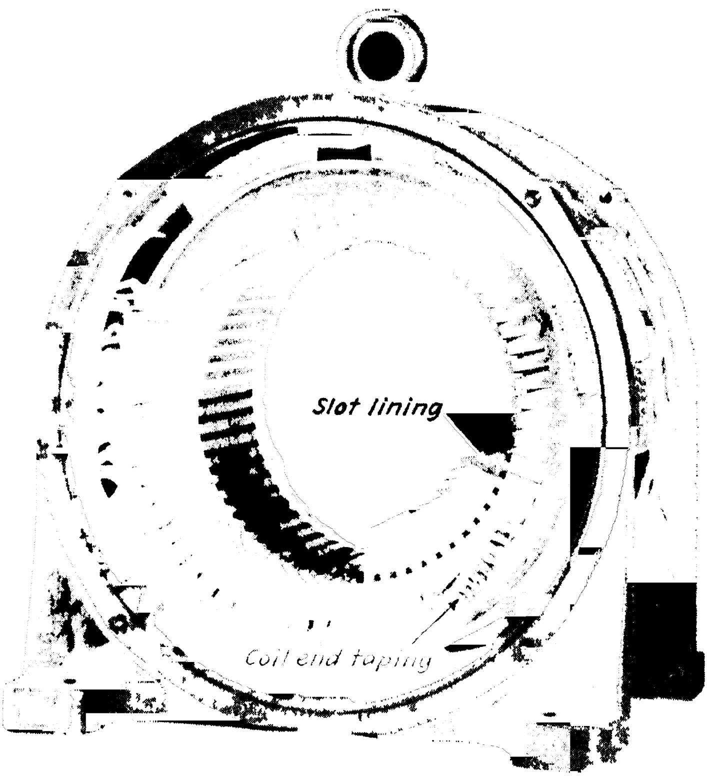


FIG. 51.—Partially wound stator of induction motor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

50 volts per mil thickness. On the basis of the total thickness (counting all insulation from conductor to iron) used for 600 volts, the stress is only 600/0.033 = 18 volts per mil. Even for 4,000-volt insulation, where three layers of wrapper are used, the stress is only $4{,}000/(3 \times 0.012) = 111$ volts per mil.

On the end windings, 0.010 in. varnished cloth tape is common as major insulation, with the following usual numbers of layers.

Up to 1,000 volts	1 layer half-lapped (2 thicknesses)
2,200 to 3,500 volts	2 layers half-lapped (4 thicknesses)
4,500 volts	3 layers half-lapped (6 thicknesses)
6,600 volts, small motors	4 layers half-lapped (8 thicknesses)
6,600 volts, large motors (3,000 hp.)	5 layers half-lapped (10 thicknesses)

The conductor insulating and the binding tape can be counted upon to a certain extent, so that the stress is still quite low on end-winding insulation.

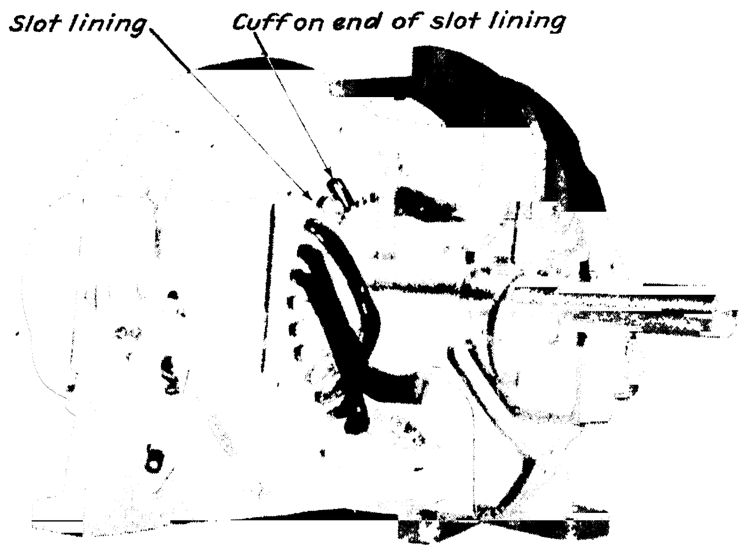


FIG. 52.—Cutaway view of induction motor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

With respect wholly to electrical factors, it should be possible to use much thinner insulation; but long experience with mechanical and thermal life properties of insulating materials makes the designer conservative.

STUBBING AND CONNECTING.—After all the coils are in place, the winding is ready for the operation called "stubbing," which means connecting the coils into small bunches or groups corresponding to the number of poles for which the motor is to be wound multiplied by the number of phases in the supply circuit. For example, assume that there are 72 slots and 72 coils and that the winding is to be connected for three phase, six poles. The

number of pole-phase groups would then be $3 \times 6 = 18$, and winding would proceed by connecting the first, second, third, and fourth coils in series by twisting and soldering together the neighboring leads and taping up the joint, or "stub," so formed between adjacent coils. This would leave the lead beginning coil 1 and the lead ending coil 4 open, representing the beginning and ending of one pole-phase group. In a similar manner, coils 5, 6, 7, and 8 would be connected in series, leaving the lead at the beginning of coil 5 and at the end of coil 8 open, to serve

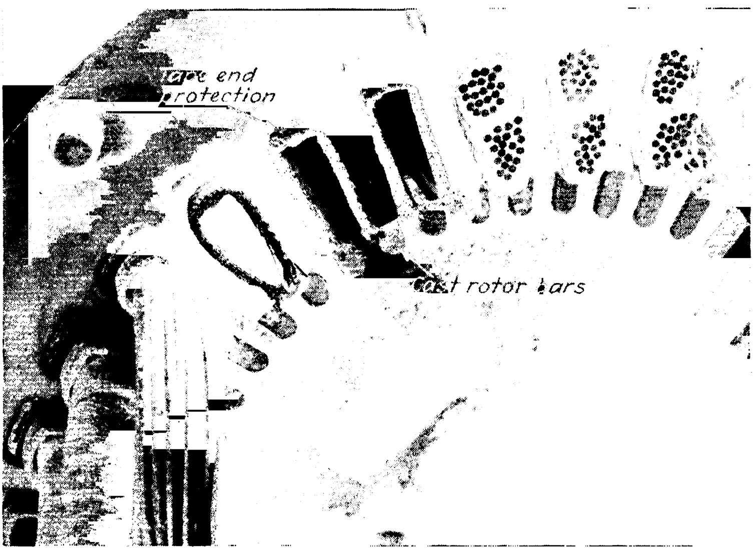


FIG. 53.—Induction motor windings. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

later as the beginning and ending of the group. This process is continued all around the machine until the coils are connected in 18 groups, each group consisting of 4 coils in series, and there are 36 leads remaining for the cross-connections. The winding is then ready to be connected.

PARTLY CLOSED SLOT WINDINGS.—The winding of a core with the partly closed slots is similar to that just described for the open slots, except that the coils are not insulated before placing in the slots, although in most cases they are formed very nearly to shape. A fully formed and insulated coil cannot, therefore, be inserted in the slot; and the individual turns must be fed in

through the narrow opening. It can be realized, then, that "ground" insulation (from coil to core) cannot readily be placed on the coil as is done in open slots. As a consequence, we do the next best thing and insulate the slot more thoroughly. A liner is usually provided that is a combination of two materials, most often fish paper (next to the iron) and varnished cloth, cemented together. Impregnation binds this together firmly.

FIG. 54.—Completed stator of induction motor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The ends of these slot liners are protected from tearing by a folded "cuff" or twine reinforcement on the edge. When the bottom coil is in place, a center wedge or insulating strip is placed above it and the upper coil is threaded in and the final top wedge driven in place. In the better classes of winding the diamond ends of the coils are taped from iron to iron [where coil leaves core to point of reentering (Fig. 53)] with insulating tape as each coil is inserted. Cotton tape is wound on each coil group

of conductors where class A insulation will serve (low operating temperature); and mica tape is substituted where class B (high-temperature) insulation is required. Diamond-shaped pieces of insulation also are placed between the ends of the coils outside the core at the points where the phases change. In many modern motors the coils, before inserting in the core slots, are wound continuously in groups, *i.e.*, without cutting the wires in passing from one coil to the next, the stub connection in the completed winding being thus avoided.

There is a definite trend toward high-temperature insulation that may be ascribed to an increase in the occurrence of unfavorable ambient conditions and overloads in motor applications. Mica, asbestos, and glass fiber, therefore, appear in more and

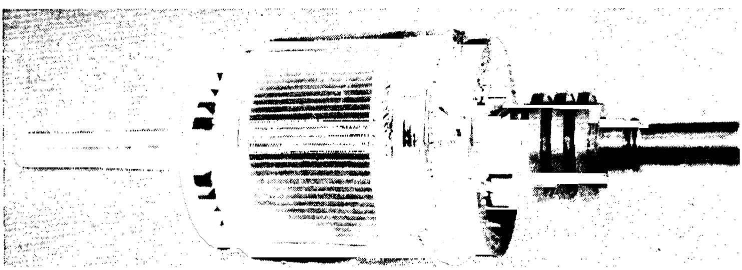


Fig. 55.—Wound rotor for induction motor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

more motors, and less cotton insulation is called for. Thus, longer life insulation capable of withstanding more severe conditions is being provided by motor manufacturers.

Rotors.—Wound rotors for induction motors involve no procedures essentially different from those already described. The conductors are usually large, and the insulation duty only that necessary for low voltage. End windings must be held mechanically by banding to resist centrifugal forces (Fig. 55).

Squirrel-cage rotors may have copper bar conductors (one to a slot), all connected at both ends by solid copper rings. The bars are given through the bar slots without insulation. Of course, the oxide on laminations provides a slight amount of insulation, so that the two ends of the conductors are not short-circuited; but there is no need for conductor insulation to ground (core). The frequency, when the motor is running, is low, and the voltage is low.

Similarly with die-cast rotors—the insulation problem is striking because of its absence. Aluminum alloy is cast, with the rotor in a mold, so that the metal forms conductors in the closed slots, end rings, and ventilating fins, all in one operation.

SLIP RINGS.—The part on alternating-current rotors corresponding to the commutator of a direct-current armature is of course the slip-ring assembly. Obviously, insulation is a simpler problem.

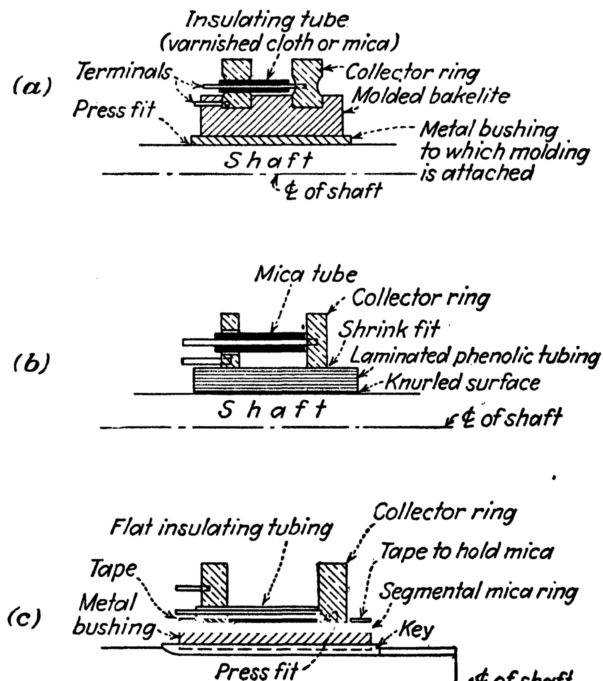


FIG. 56.—Collector-ring insulation.

Where mechanical stresses are low, the rings (of iron for the rotating field of alternators or bronze for alternating-current collection) are held to and insulated from a steel bushing by molding, plastic molding mixtures such as Bakelite and wood flour being used (Fig. 56*a*). In structure Fig. 56*b*, we start with a laminated phenolic tube which has rings shrunk on the outside by heating the rings and pressing on to the tube. When the rings cool, a tight fit results. The shaft is knurled, and the insulating tube pressed on.

The method used for larger rings starts with a steel bushing having a keyway for fastening to a shaft (Fig. 56*c*). Over this is placed mica insulation in three circular sectors, and the rings are pressed over the mica.

Since the connections to the rings come from one side (from the rotor), insulated passages through successive rings must be obtained. In small rings, studs extending from the inside ring through to the required other rings are used with insulating tubing over the stud. For high currents, strap conductors are frequently welded to their respective rings. These pass through the web section of other rings, encased in flattened insulating tubing.

Summary.—Other machines, such as synchronous motors and alternators, might be described; but they use elements common to the machines already covered. For example, an alternator consists of a field like that of a direct-current machine and an armature, the coils of which are the same as those of a direct-current armature; but instead of a commutator we substitute a slip-ring assembly. The elementary forms of insulated parts, for motors and generators, that are different enough to warrant classification are as follows:

a. Armature coils, with slot insulation (stator coils are the same, except that they are inside out with relation to the core. Wound rotors are also similar).

b. Field coils.

c. Commutator.

d. Slip rings.

e. Brush rigging.

We shall see that many common types of rotating machines can be synthesized from these five elements, as follows:

Direct-current generator or motor	*a*, *b*, *c*, *e*
Squirrel-cage induction motor	*a*
Wound-rotor induction motor	*a*, *d*, *e*
Repulsion induction motor	*a*, *c*, *e*
Synchronous motor	*a*, *b*, *d*, *e*
Alternator	*a*, *b*, *d*, *e*

CHAPTER VI

LARGE ROTATING MACHINES

Large Direct-current Machines.—Rarely are direct-current motors or generators designed for voltages above 1,500. The insulation involved therefore is not considered "high-voltage" insulation and is similar in many respects to that of small direct-current machines.

ARMATURE COILS.—The starting point in insulating the armature is the individual conductor, which is frequently rectangular in section. If the machine is intended for class A service (low temperature), double cotton covering is used. When class B insulation is required, asbestos covering is provided, for conductors of moderate size. This may be applied in two ways, either

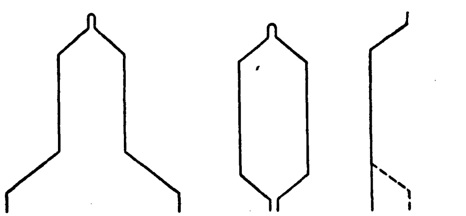


FIG. 57.—Coil forms for large motors.

as a felted asbestos covering or as a wrapping of asbestos-paper tape. On large bars, mica tape is often used. It is essential that the turns be held rigidly together and be smooth and regular in dimensions so as to fit well in the slots. For this purpose the slot portion of large coils is usually bakelized, which is a process of impregnation of the conductor covering with Bakelite varnish and forming under heat and pressure to final dimensions. Over the coil a mica wrapper is added for "ground" insulation. The number of turns of the coil wrapper depends on the voltage to ground. In machines intended for 600 volts or under, 1½ turns of coil wrapper (the half turn is to ensure overlapping on the top of the coil) is sufficient; and for 1,500 volts 3½ turns may be

required. A layer of cotton tape holds the wrapper in place (binder insulation).

In large machines, coils are actually not complete circuits as wound, but half coils. They are really coil sides (slot section) with projecting ends of the familiar partial diamond shape for connecting later outside the armature body to the commutator necks at one end and to other coil ends at the other end of the armature (Fig. 57). The coil ends are insulated with mica tape

FIG. 58.—Placing coils in large direct-current generator. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

and finished with one layer of butted tape (no overlap) (Fig. 58), cotton tape for class A and asbestos tape or glass-fiber tape for class B insulation.

SLOT INSULATION.—To line the slot, a fish-paper cell gives sufficient mechanical protection to the coils, which themselves have ample insulation. The same material is used for the separator in the slot between bottom and top coils, unless high temperatures in the iron are expected, when a heat-resisting grade of phenolic impregnated sheet is inserted. The same phenolic laminated sheet may be used for slot wedges, also, although for most purposes fiber wedges are usual.

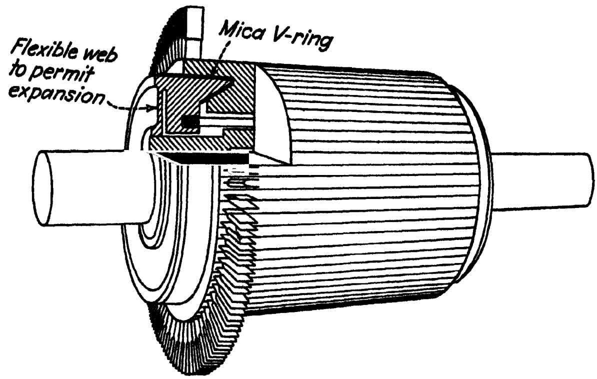


FIG. 59.—Commutator construction. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

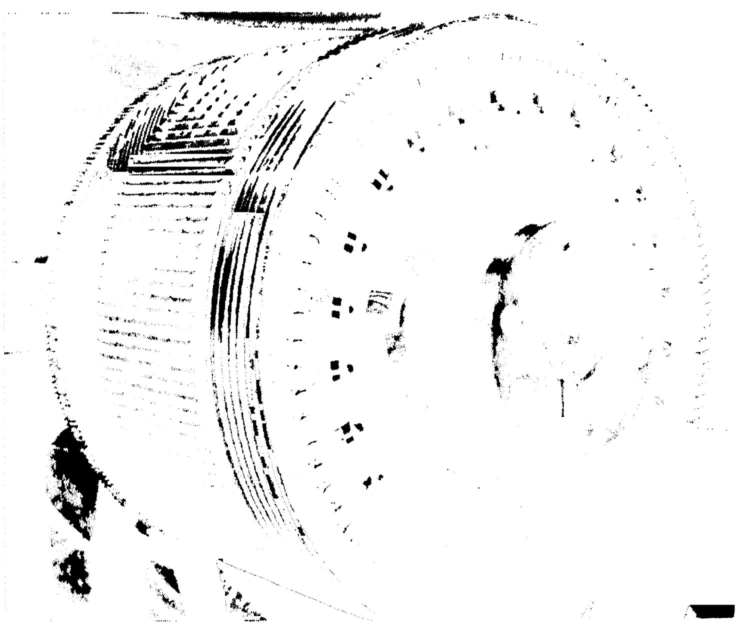


FIG. 60.—Large direct-current armature. Banding on rear end, commutator end incomplete. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

We observe again that the insulation of coils for rotating machines follows a definite pattern: first, conductor insulation; then, ground insulation; third, slot insulation.

COMMUTATOR.—The mica-plate pieces between commutator bars are essentially the same as in small machines, except that the control of dimensions and properties is a magnified problem. The mica must be carefully gauged and selected so that the

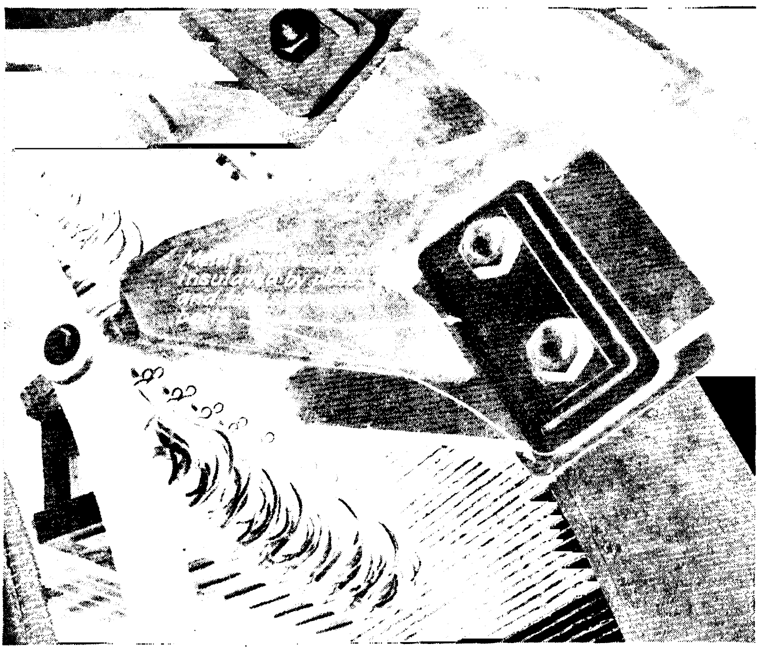


FIG. 61.—Large direct-current machine brush support. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

completed circle of mica and copper is accurate in circumferential spacing and will fit the V-ring or other type of support as intended. The V-ring insulation must withstand great pressure. A molding mica, quite similar to that used in small commutators, is formed with heat and pressure into segments, placed between the V-ring and the copper (see Fig. 59).

Most armatures are banded at both ends with tinned steel wire wound over a layer of varnish-treated duck cloth and securely soldered together (see Fig. 60).

Brush-holder supports are insulated with plates of fiber and tubes of fiber over the bolts, as shown in Fig. 61.

Where collector rings are required, as in three-wire direct-current machines, the rings are bolted to a supporting spider on the shaft (large diameter), insulating tubing being used over

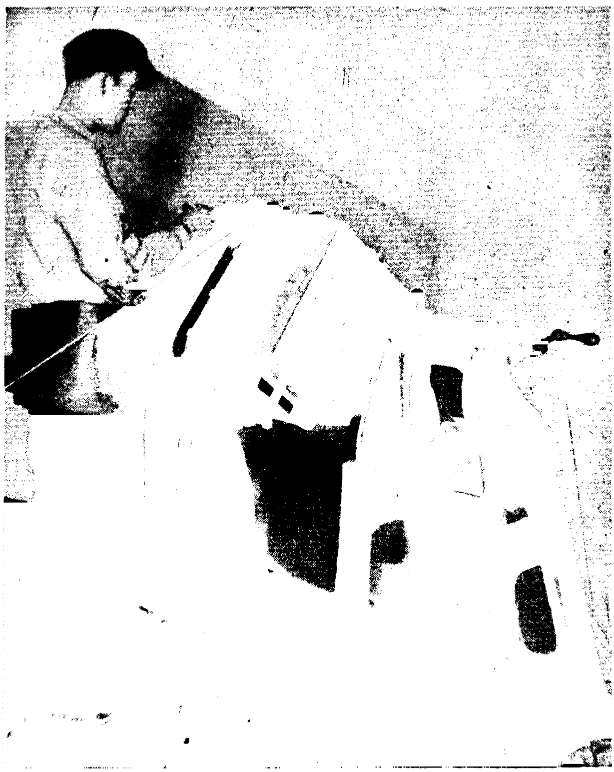


FIG. 62.—Field coil for large direct-current machine being wound directly on pole. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

the bolts and washers under the heads. Small rings may be shrunk on insulated (mica or phenolic tubing) steel bushings.

FIELD COILS.—Shunt-field coils are frequently wound on the assembled pole as a form. A layer of pressboard is wrapped around the iron, and the double-cotton-covered wire wound on as the pole is rotated in a special holder (Fig. 62). For high temperatures, asbestos or glass-covered wire is substituted, and

mica used against the iron. An insulating spacer (often of hardwood) next to the pole tip keeps the coil in place, and an insulating-varnish coating on the coil keeps out moisture and dirt. No tape or other covering is placed over the outside of the wound coil.

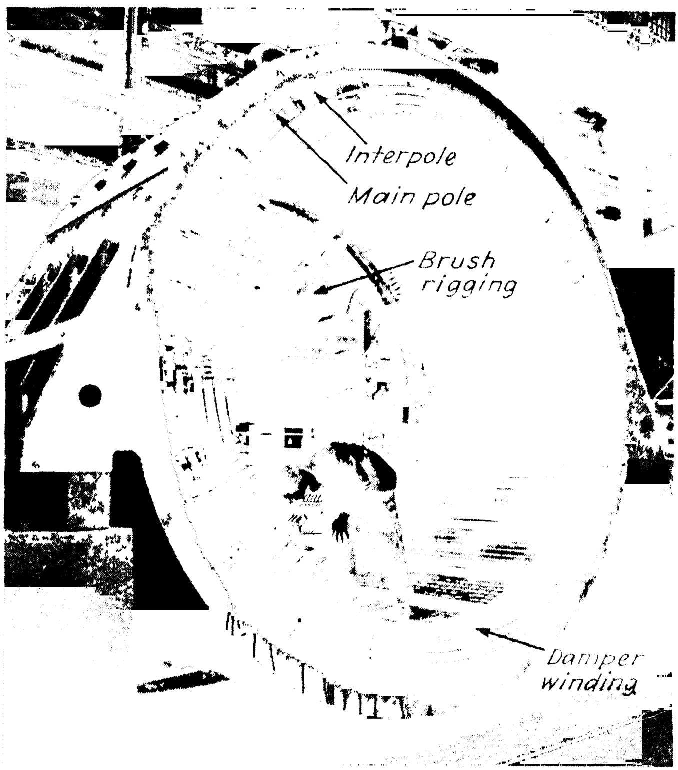


FIG. 63.—Large direct-current machine showing field coils. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Series-field coils are wound of bare strap and supported free of the poles and shunt coils by laminated Bakelite hangers which are rigid and preserve insulating and ventilating spaces around the strap coil.

Also of bare strap are the interpole field coils, usually spaced with pressboard strips and held away from the frame by impregnated wood blocks (Figs. 63, 64).

BEARINGS.—An interesting problem in large alternating-current machines is that of bearing currents. Frequently it is impossible to balance completely the magnetic effect of end connections and wiring around the frame. With heavy current flowing in some of these external conductors, a current is induced in the shaft-bearings-bedplate circuit. Although the potential is very low, sometimes large values of current are present that damage the bearing surfaces. Journals on the shaft may become so badly pitted that excessive heating occurs and the shaft must be refinished, an item involving considerable expense and delay in connection with a large machine. It has been found that insulation should be provided whenever the possible ampere turns around the shaft exceed 3,000.

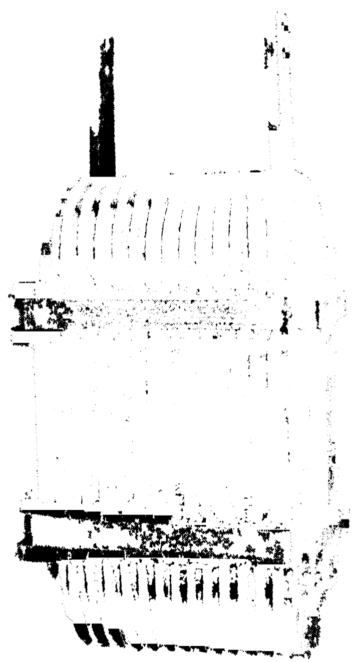


FIG. 64.—Interpole field coil. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Usually there are three points at which some insulation is placed to avoid this trouble. First, one or both bearing pedestals are set on a layer of fiber, about ⅛ to ¼ in. thick. Since many large pedestals are lined up by dowels, the dowels must also have fiber tubing over them (Fig. 65). The second location is the oil piping, if forced lubrication for starting or running is used. At the machine, a molded insulating pipe coupling is inserted. Third, if the bearings are water-cooled, the water line must have a similar insulating coupling.

Large Alternating-current Machines.—We may, for a discussion of insulation, group large alternating-current machines as follows: (1) induction motors (usually with wound rotor), synchronous motors, and alternators driven by motor or engine; (2) water-wheel alternators; (3) turboalternators. As with

smaller (industrial) sizes of machines, there are many special designs that do not follow the general methods, but we shall limit our attention to normal, commonly used practices.

INDUCTION MOTORS.—*Stator coils* are wound of double-cotton-covered conductors (sometimes paper covered for large sections). Coil insulation in the slot portion consists of a paper-mica wrapper (ground insulation) held on by a butted layer of cotton tape. End turns are taped with varnish-treated cloth with a half-lapped layer of cotton tape over it. A coil thus insulated must be thoroughly impregnated with a protective material, insulating varnish, for example. One method of applying this

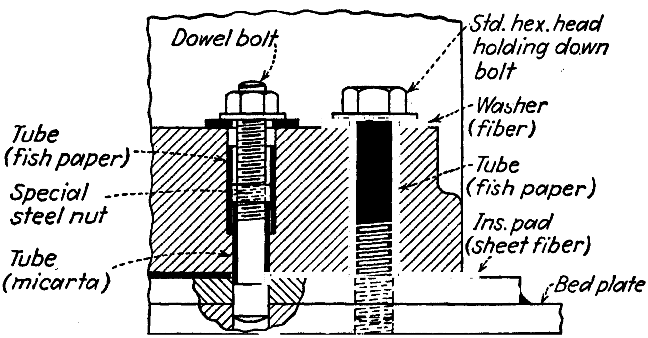


FIG. 65.—Bearing-pedestal insulation. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

treatment is to varnish-dip the coil before and after the final taping. Another method is to accomplish complete penetration in one varnishing operation, by impregnating under vacuum and then forcing the varnish into the coil by application of pressure. Solventless varnish is very effective for this treatment and eliminates the necessity of solvent removal in drying and baking. Before placing the finished coils in slots, a slot liner of fish paper is inserted, largely for mechanical protection during assembly of coils in the iron. The practice described above is followed for class A (low-temperature) applications. For class B (high-temperature), there is a substitution of materials. The conductors may be insulated with either glass yarn or asbestos for low voltages and mica tape for high voltages. The coil insulation ("ground insulation") is a mica wrapper, held on with glass tape or asbestos tape (binder insulation). End turns have mica tape.

Here, again, the whole coil is varnish-treated as before. For class B, it is not usual to provide a slot lining.

On the end windings, a soldered joint usually occurs at one or perhaps both ends of the machine. These stubs have to be covered with insulation in some manner. One scheme is to cover the open ends with a cloth boot or bag and then apply tape over the outside.

Where adjacent coil ends have full line potential between them (as at the end of a pole group), an extra layer of tape (treated cloth or mica) is applied, a practice having its counterpart in windings of smaller induction motors where pieces of sheet insulation are usually inserted and taped in.

Coil wrappers may have 1½ to 4½ turns, depending on the voltage of the machine. Typical practice is shown in Table XIII.

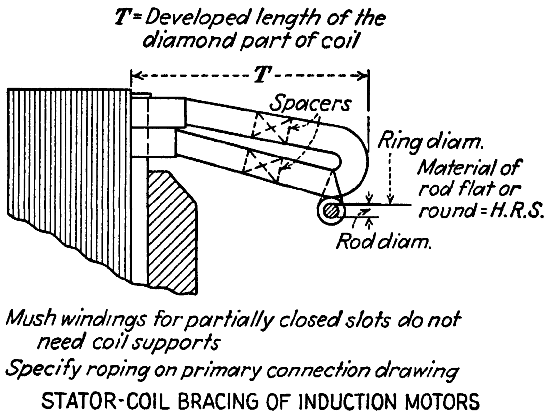
TABLE XIII

Voltage	Slot portion		End windings	
	Wrapper thickness in.	Number turns	Tape thickness, in.	Number layers half lapped
Fish Paper and Mica				
600	0.012	1½	0.010	1
1,200	0.012	2½	0.010	1
2,500	0.012	3½	0.010	2
Varnished Paper and Mica				
3,500	0.015	3½	0.010	3
4,500	0.015	4½	0.010	4
6,600	0.015	4½	0.010	5

The coil ends of large machines require bracing to withstand mechanical vibration and magnetic forces resulting from sudden load changes. One form of bracing is a steel ring, well insulated with tape, supported rigidly from the frame. To this ring, the separate coils are taped or laced securely (Fig. 66).

The *rotor* has to withstand severe mechanical and electrical stresses and therefore must be very well constructed. It is usual practice to insulate rotor coils for double normal voltage. In

contrast to small induction motors, the voltage present in large rotors may be quite high—up to 4,000 volts in some sizes. For strength against centrifugal forces, a partly closed slot or an overhung slot shape may be used. In such rotors a full coil



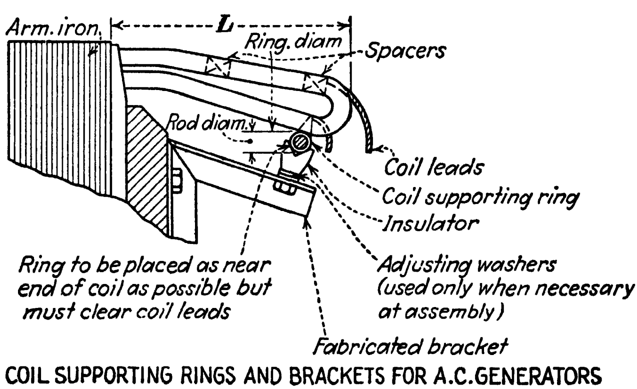


FIG. 66.—Bracing of coils. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

cannot, of course, be inserted. Form-wound coils are used as in the stator, but only one bar wide, so that two such coils can be slipped into the coil side by side (Figs. 67, 68). Each bar is fully insulated to ground so that no outer coil insulation is

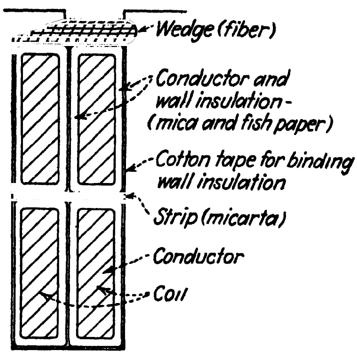


FIG. 67.—Overhung rotor-slot of 3,000-hp. induction motor. Class A insulation. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

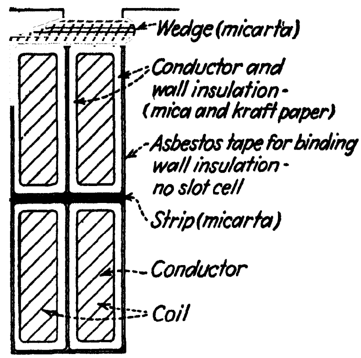


FIG. 68.—Overhung rotor-slot of 2,500-hp. induction motor. Class B insulation. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

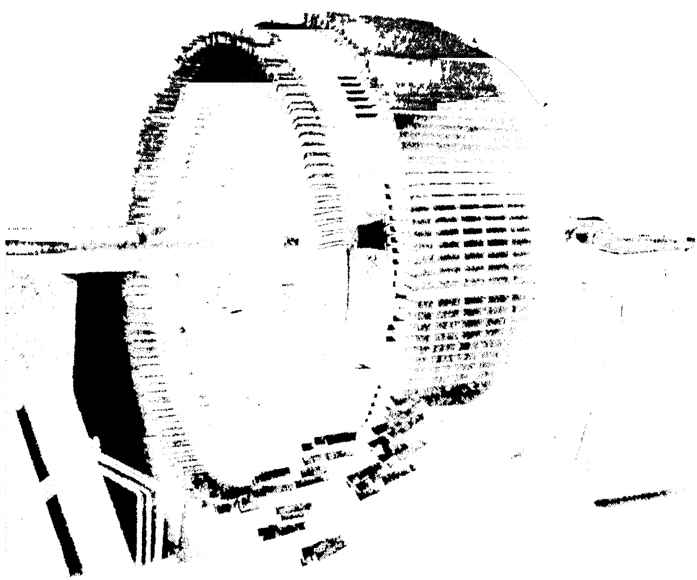


FIG. 69.—Partly wound rotor for large induction motor. Fully insulated coils being placed in slots. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

required, except the usual paper liner for the slot. The details of insulation (conductor, wrapper, tape) are of the same type as for the corresponding stator. Fiber wedges close the top of the slots (Fig. 69).

A "pushed-through" winding is sometimes used, and in this case insulated half-coils are formed. After insertion, the straight ends are bent to shape and both ends soldered to other half-coils.

In place of the bracing ring used on stators, banding of the rotor at both ends holds the coil ends in place. The banding wire

Fig. 70.—Collector rings for induction motor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

is wrapped over heavy treated duck and soldered together completely. An inner coil support on the spider is required so that the banding will not collapse the coil ends.

After the rotor is wound, connected, and banded, a final insulating finish is applied. This sealing operation is accomplished by dipping the whole rotor in an insulating varnish and drying, preferably by baking. The choice of varnish is dependent on the service intended. Resistance to moisture, resistance to oil, and resistance to chemicals may demand different treatment.

For steel-mill motors, where dirt and metal dust may be added to other evils, some customers prefer an insulating finish that can be cleaned readily and will indicate when it is dirty. For this, a bright-red finish containing glyptal resin with iron oxide is frequently used.

Collector-ring construction is similar, except in size, to that used on smaller machines. A common form is a steel bushing, wrapped with mica over which the rings are pressed or shrunk.

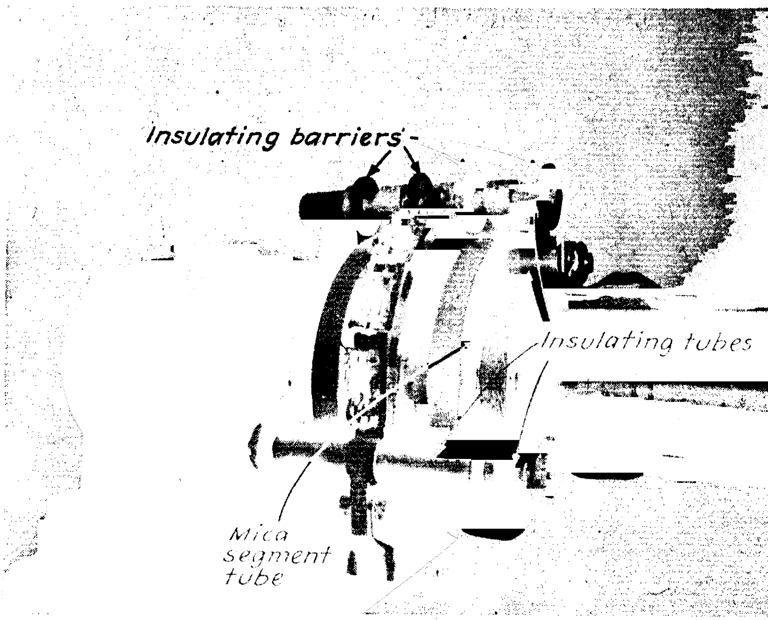


FIG. 71.—Collector rings and brush rigging for large inductor motor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Connections to the several rings may be made by studs with insulating tubing (Fig. 70).

Brush rigging is also similar to that described before and shown in Fig. 71.

SYNCHRONOUS MOTORS. *Stator.*—Many large synchronous motors are built for relatively low speed, and the revolving field, therefore, is large in diameter and carries many poles. The armature (stationary) is short in axial length compared with those of other kinds of motor (Fig. 72). Armature coils are insulated as for induction-motor stators, except that the propor-

tions between the length of slot portions and coil ends may be different. Higher speed motor stators may closely resemble induction motors.

Field Coils.—It is now common to wind field coils directly on the poles. Two U-shaped cells of pressboard are opposed to cover the iron, and the wire is wound over this. For class A

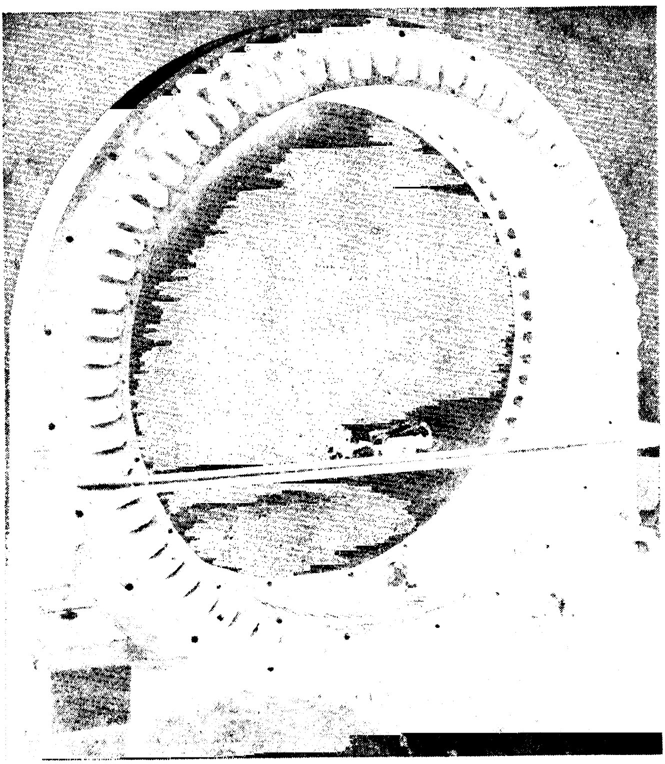


FIG. 72.—Low-speed synchronous-motor armature. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

insulation, cotton- or paper-covered wire is used, varnish being applied between layers and on the outside of the coil. No other covering of the coil is needed. Adjacent to the pole tip a spacer of varnished treated plywood is inserted to hold the coil in place and provide creepage distance to the ground.

Field coils that have long sides may require added treatment to hold them rigid. Application of phenolic varnish, pressing,

and baking gives the desired stiffening. When high-temperature insulation on field coils is needed, the U-shaped cells next to the iron are made of asbestos or mica, the wire covering is asbestos or glass, and the pole-tip spacer is made of heat-resisting laminated insulation.

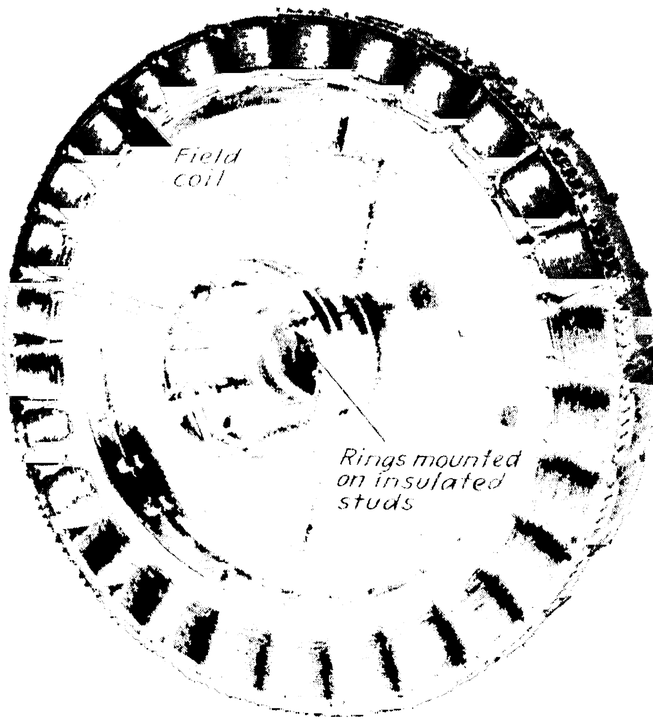


FIG. 73.—Low-speed synchronous-motor field (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

High-speed synchronous motors will have smaller diameter and in general longer rotating fields. The field coils are fewer in number and are thicker and heavier than on slow-speed motors. The coils may be wound on forms, slipped over the poles, and wedged in place by spacers.

MOTOR- OR ENGINE-DRIVEN ALTERNATORS.—This class of machine is distinguished from turboalternators (described below) by lower speed (for the same capacity). Their elements (arma-

ture, field, etc.) are substantially the same as the motors and generators already described, at least with respect to insulating construction, so that no special description is necessary.

TABLE XIV.—REPRESENTATIVE DESIGN PRACTICE
(Armature-coil insulation—Salient pole generators and synchronous motors)

	6,600 volts (inches)	11,000 volts (inches)	13,200 volts (inches)
Laminated phenolic fabric	0.090	0.140	0.172
Cotton tape	0.007	0.007	0.007
Mica tape	0.020 0.0075	0.020 0.0075	0.020 0.0075
Total	0.1245	0.1745	0.2065

WATER-WHEEL GENERATORS. *Stator.*—Structurally, generators built for water-wheel drive are unlike other generators in

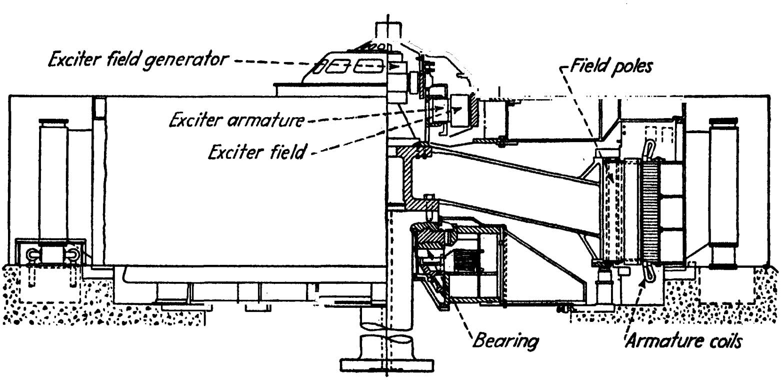


FIG. 74.—Section of water-wheel generator with "umbrella" field for Norris Dam. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

that they are most frequently vertical machines of low speed and large diameter. The stator may have an inside diameter of 40 ft. or more. The core of the stator is built up of segmental sections clamped between heavy end bracket members forming part of the machine frame. Most frames are now built up of welded steel plates, outmoding the former heavy steel castings. Although the shape of the stator of water-wheel generators is quite different from that of turbogenerators, the insulating practice is substantially the same. The core length (or height) is

short in a water-wheel machine, and the diameter large. For a turbine-driven generator, the core length is great and the diameter small.

Rotor.—The two types of field, umbrella and conventional, are shown in Figs. 74, 75. In the former the spider and poles are above the main upper bearing, an arrangement that gave rise to the name. The field coils are similar for both types.

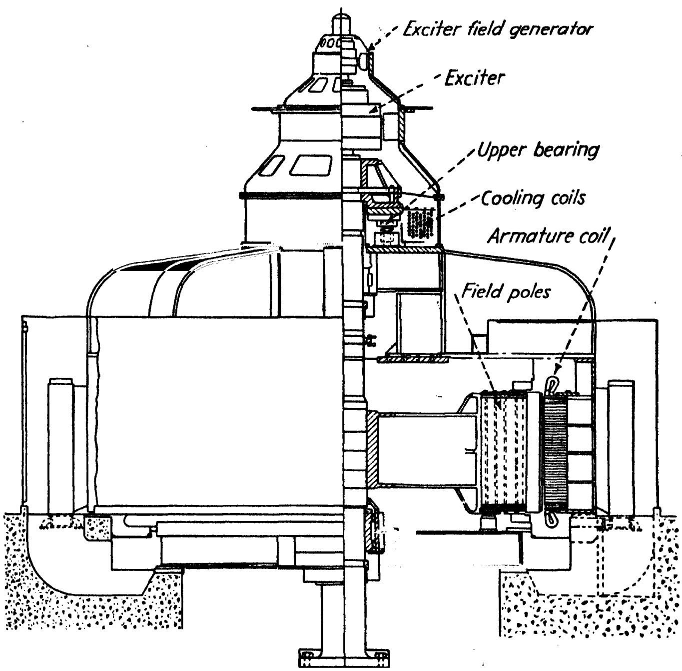


FIG. 75.—Section of water-wheel generator with conventional field for Boulder Dam. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The field conductors are large and consist of copper strap wound on edge, as can be seen in the representative coil construction shown in Fig. 76. Mechanical stresses due to high peripheral speed require a strong insulating structure, with mica next to the core, protected on the ends by asbestos cloth. A laminated Bakelite washer at either end of the coil offers mechanical support and insulation from the iron. The coils are held firmly in place by springs, either flat or radial spiral springs set in recesses in the spider, as in Fig. 77.

Sometimes the problem of removing heat from the field coils requires special consideration. A form of coil that offers both

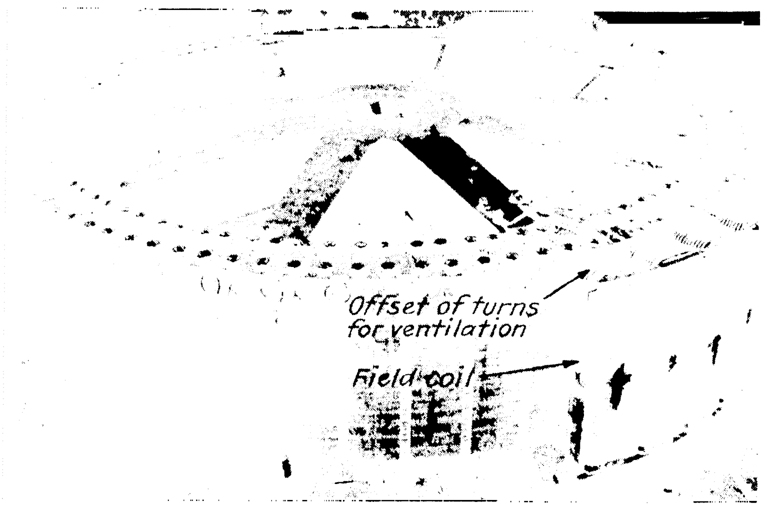


FIG. 76.—Vertical water-wheel generator field under construction. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

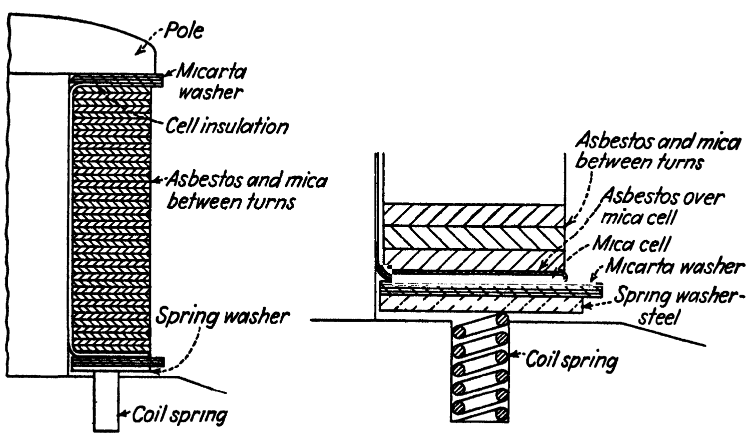


FIG. 77.—Section of water-wheel generator field coil. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

increased coil surface and a fan effect (Fig. 78) has adjacent turns wound on steps so that the turn diameter is larger and the outer edges project like fins.

TURBOALTERNATORS.—Turboalternators are also peculiarly proportioned machines, compared with small motors and generators. The whole machine is usually enclosed in a casing which directs the necessary cooling air; the core is long, perhaps 15 to 20 ft.; the rotating field looks like a solid cylinder (no salient poles showing) and, for a 3,600-r.p.m. 25,000-kva. machine may be only 3 ft. in diameter. The core must have frequently spaced ventilating ducts through it, and this means that at the ducts

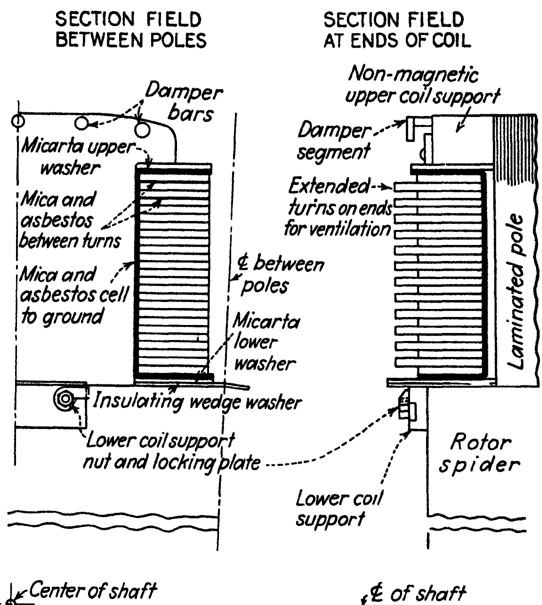


FIG. 78.—Section of field coil with ventilated turns. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

the coils in the slots are unsupported. A 20-ft. bar of copper, operating at high temperatures in an iron slot, moves appreciably and may cause damage to the coil insulation if the design is not correct. Alternate temperature extremes cause some types of composite insulating materials to swell and form air pockets. This must be avoided, especially on high-voltage machines, because of the possibility of corona in the voids, a problem to be considered in more detail below.

We therefore have an unfortunate combination of high voltage, high temperature, and mechanical difficulties assignable to the

length and size of coils, challenging the best talent that designers can muster. Probably more research has been expended on insulation of turbogenerators than on that of all other rotating machines combined. It should be noted that no other electrical device is built in capacities of single units so large as those of turbogenerators, ratings above 100,000 kva. being not at all uncommon.

Armature Coils.—Starting with the stator winding, we again meet the same terms as in the discussion of motor windings,

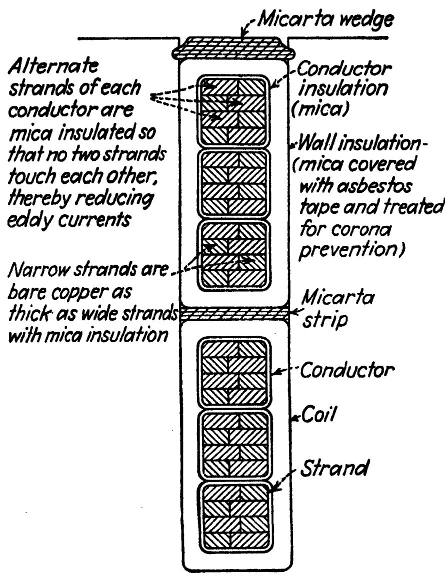


FIG. 79.—Section of generator armature coil with overlapping conductors. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Chap. V, conductor insulation and coil insulation (sometimes called ground insulation). The required cross section of copper in a conductor may be several square inches. For two reasons this could not be solid: (1) because of impossibility of bending solid copper to shape; (2) because of eddy-current losses. Each conductor, therefore, consists of several individual elements known as "strands." These may be square or strap copper. Strands of unequal width are sometimes used, especially in water-wheel stators, wherein the wider bars only are insulated. The narrow strands are bare and as thick as the insulated wide

strands. Therefore, the insulated wide strands overlap in successive layers, so that the bare strands do not touch and thus all strands are separated to accomplish a reduction of eddy currents (Fig. 79).

Figure 80 indicates the location of strand, conductor, and coil insulation. Strands are wrapped with class-B tape, either asbestos or glass, and assembled in groups to form conductors,

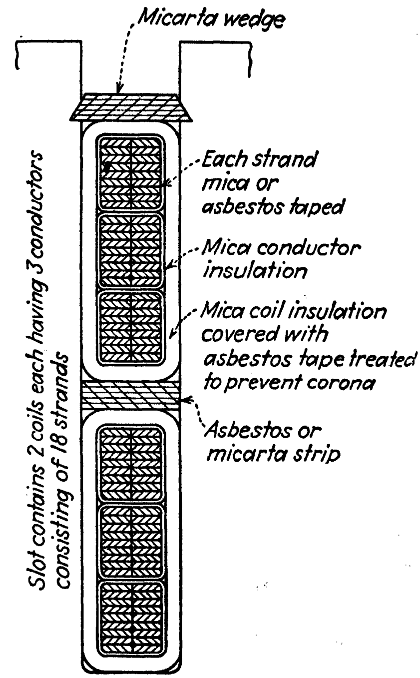


FIG. 80.—Section of turbogenerator armature coil. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

which are then wrapped with mica tape. The conductors are treated, on the slot portion, with phenolic varnish, pressed, and baked before assembling into coils. Most important is the ground insulation formed of another type of mica tape (with an asphaltic bond). The characteristics required for the coil tape are: (1) sufficient flexibility to withstand handling during assembly; (2) low dielectric loss; (3) resistance to swelling at the ventilating ducts. The insulated coil is impregnated by vacuum

and pressure methods with an insulating varnish. Then, finally, over the slot portion a layer of heavy asbestos tape is applied.

TABLE XV.—TURBO INSULATION
(Representative working stresses in major insulation)

Operating voltage to ground in Y-machine (conductor insulation neglected)	1-turn coils, volts/mil	Multiturn, volts/mil
6,600	33	30
11,000	39	37
13,200	41	38
16,500	43	39
22,000	44	40

TABLE XVI.—TYPICAL TURBO INSULATION
[Deep coils (1 × 4 to 1 × 10). Turns wide × turns deep]

Rated Voltage	Total Insulation Thickness, Copper to Iron, In.
4,500	0.1255
6,600	0.1455
11,000	0.1955
13,200	0.2275

If there is an air pocket between the outside of the coil and the iron of the slot, we have two dielectrics (air and mica tape) in series with widely different dielectric constants. The air takes most of the stress and may ionize. Corona in the slot will ultimately cause failure of the insulation from rapid oxidation and attack of nitric acid. Frequently, such a breakdown has the appearance of a wormhole, with evidence of surface erosion, also. An effective remedy is coating the coil surface with a semiconductor. A graphite paint known as Aquadag is excellent for this purpose; it is applied over the outside asbestos tape for a distance somewhat longer than the slot length. Even though the coil is not touching the slot at every point, the surface is thus intimately and effectively grounded by the coating, which is sufficiently in contact with "ground." There is no slot-cell lining used. Sometimes, if the coil is not a tight fit in the slot, mica strips are driven in on one side, the other side of the coils thus being wedged against the iron. A filler strip of laminated

phenolic insulation is inserted between the coils and the slot wedge of the same material.

End Windings.—The end windings require very strong mechanical bracing to resist short-circuit stresses. Arrangement of coil connections and end turns often seems to be a complex yet

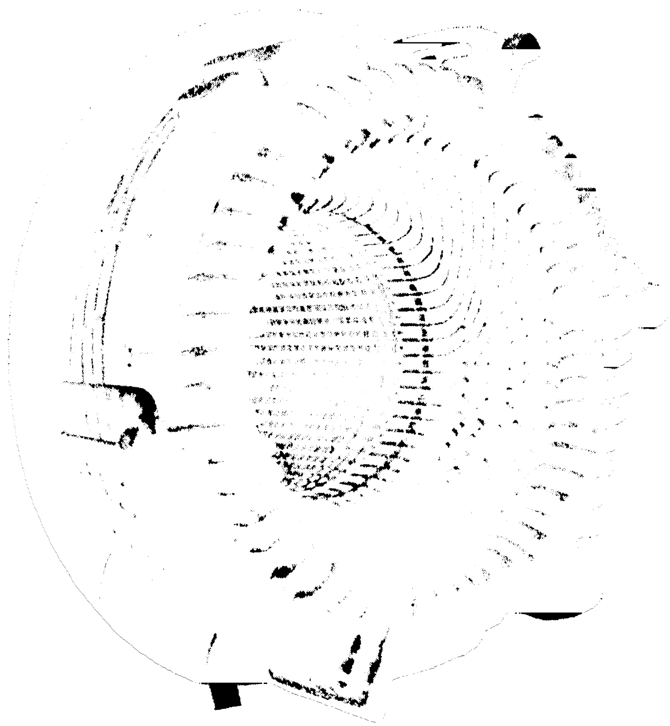


FIG. 81.—Coil end windings, turbogenerator. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

orderly network of insulated coils, cleats, braces, cord lashings, and spacers, forming an interesting geometric pattern (Fig. 81).

Various schemes are used for fastening the end turns. Spacers or separators of insulating material (fiber, wood, or laminated phenolic plate) are placed at frequent intervals between adjacent coils, and the coils lashed with strong cord to braces. Laminated phenolic brackets may be used for fastening (Figs. 81, 82), or sometimes an insulated ring (taped) supported on brackets may

serve for lashing the coils. Clamps or cleats spaced radially are also sometimes attached to provide added rigidity against movement or collapse of the coils.

We have described how the destructive action of corona is prevented in the slots in two ways: first, by compression and baking of the coil to make it solid; and second, by coating the outside with a conducting paint. Now, when we come to the end windings, we face another problem. The surface gradient at the con-

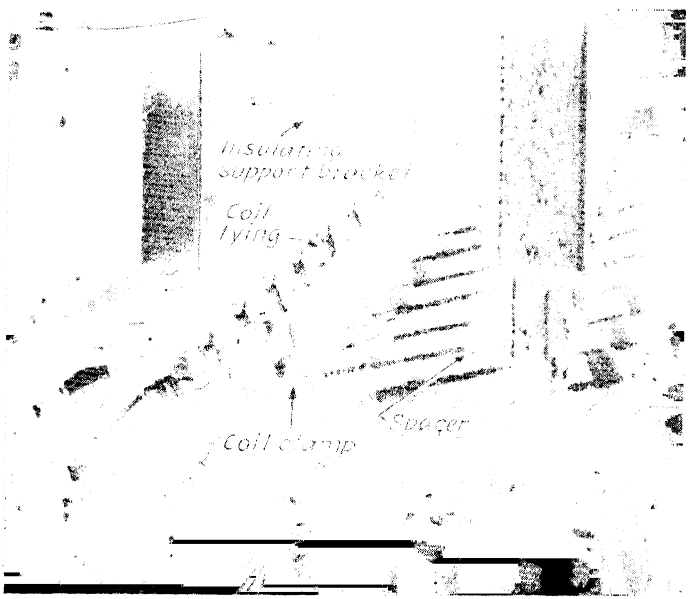


FIG. 82.—Turbo coil bracing. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

ductors is high, even with the core some inches away; and, in addition, full potential exists between adjacent portions of "phase coils." There is the practical difficulty of insulating the end turns with no included voids. The insulation at this point cannot be compressed, because of the irregular shape. The best job of hand taping and filling between layers with varnish does not ensure the density throughout the life of the machine that can be obtained in the straight portion. If the machines were small enough, vacuum impregnation after connections are made and taped would help. Many large machines are built up (the

iron and coils) at the point of installation, and a vacuum treatment of the whole generator under these conditions could not be provided. Some engineers have proposed and worked out designs for oil immersion of stator windings, by making an annular cylindrical tank from the air gap outward. The practical difficulties are apparent. The usual procedure on end windings is to apply additional mica taping, well varnished, particularly at

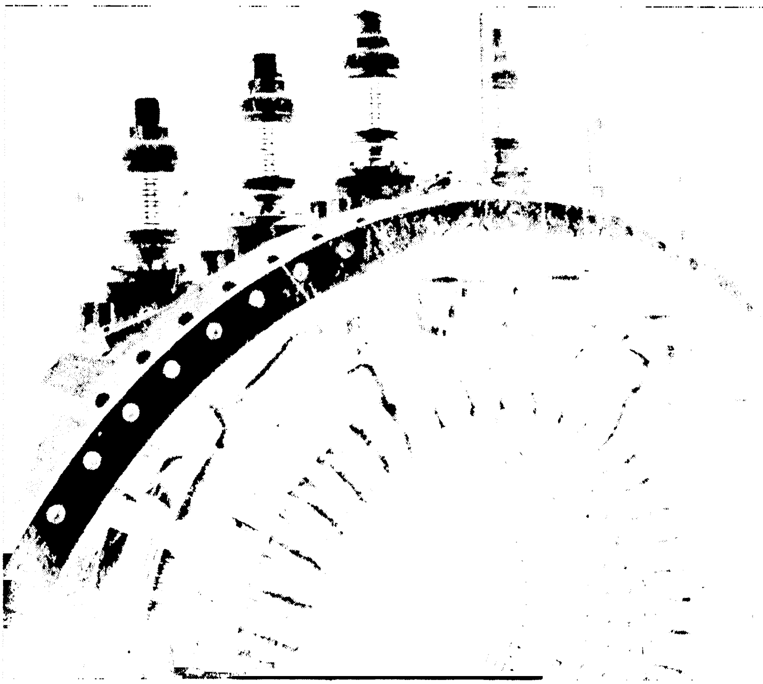


FIG. 83.—Terminals and coil ends of hydrogen-cooled turbogenerator. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

points of greatest potential difference. The last layer is asbestos or glass binding tape, coated with varnish. Besides this, the configuration of the end turns is designed so that maximum spacing between "phase coils" is obtained.

Surges on Generators.—It is not uncommon for lightning or switching surges to travel from transmission lines back into turbogenerators. Protective devices, such as lightning arresters, may give the desired protection, but only if properly placed.

For adequate protection it has been found[1] that arresters both at the machine and at a point 500 to 1,500 ft. distant are required. When cables are substituted for transmission lines, only switching surges are possible; but even these may subject parts of the winding to double voltage or more. Incredible though it may seem, surges have been found to pass through high-voltage transformers and proceed to the connected generator. Calvert has represented a generator winding by the equivalent circuit of Fig. 84.

The coils have resistance, self-inductance, mutual inductance, capacity between turns, and capacity to ground, as indicated. Initial distribution of surge potential is determined by capacity relations, but subsequent values are modified by the inductance

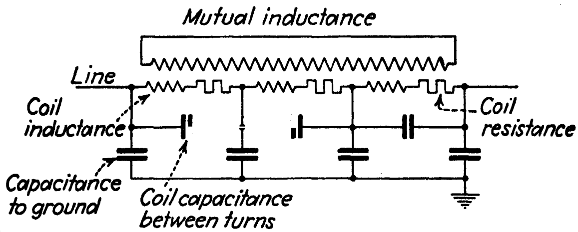


FIG. 84.—Equivalent circuit of turbogenerator. (*Calvert.*)

and resistance. Furthermore, it has been noted that internal oscillations take place, subjecting the windings to high voltages between turns. Even with the neutral grounded, a potential higher than the terminal potential may occur halfway between line and ground. If we could rely on a high impulse ratio (surge breakdown divided by normal-frequency breakdown), the condition would not be too serious; but the ratio for usual turbo-coil insulation is only 1.2 to 1.5. It is therefore imperative that relief devices in the form of gaps or arresters be installed. Another remedy lies in decreasing the steepness of wave front, which may be accomplished by shunting capacitors, connected at the generator terminals.

Turborotor (Field).—The field winding for turbogenerators is laid in slots, machined in the solid forged rotor body, and so spaced as to form salient poles as required. Since turbines are

[1] CALVERT, J. F., A. C. MONTEITH, and E. BECK, "Protection of Machines against Surges," *Elec. Jour.*, vol. 30, p. 91, 1933.

inherently high-speed machines, the number of poles in the generator rotor is usually either two or four, corresponding to 3,600 r.p.m. or 1,800 r.p.m. (for 60 cycles). An essential requirement of the field insulation is that it withstand high temperatures. Heat developed in the rotating field must be removed chiefly in a radial direction across the air gap and out through vents in the stator core. The opportunity for heat dissipation at the ends is

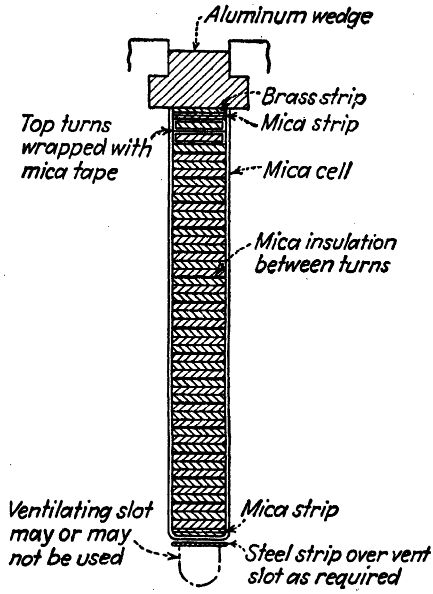


FIG. 85.—Section of turbogenerator field coil. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

slight, although full advantage is taken of this means by the addition of fins or vanes on the rotor. The maximum permissible operating temperatures are therefore usual.

Mica sheet, sometimes reinforced with asbestos cloth, is placed in the slot into which the turns are built. The conductors are bare copper strap, the full slot width, laid flat, one turn above another. Between conductors, mica strips are laid or pasted to the conductors, and in this manner the individual turns are inserted until the last few turns are reached. Mica tape is applied to these as additional insulation and protection from the metal

wedge driven in to hold the coil. The wedge must be non-magnetic and is usually brass or aluminum. Before driving the wedges, the coils in the slots undergo a long baking and pro-

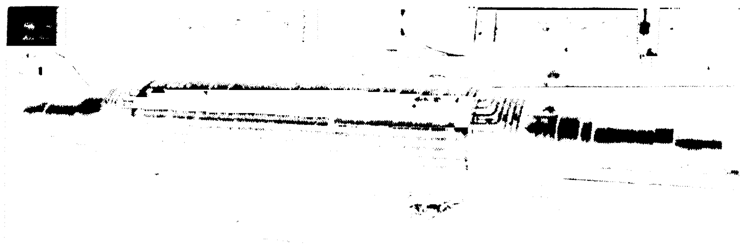


FIG. 86.—Field of turbogenerator, without retainer rings over coil ends. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

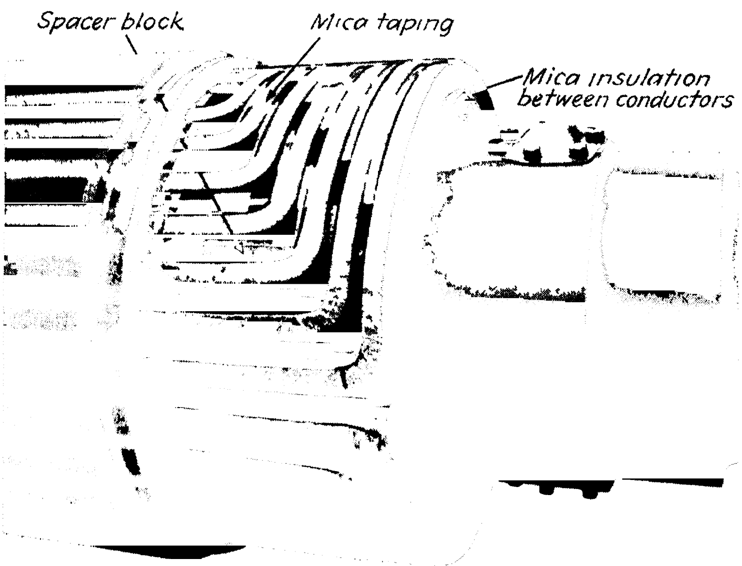


FIG. 87.—Ends of field coils, turbogenerator. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

gressive compression by special tools until the coil is dense and well cemented together.

The outer turns of coil ends are finished with mica or glass tape and spacing blocks of laminated Bakelite placed between coil

sections. Over the end turns a retaining ring or shroud of high-strength steel (sometimes nonmagnetic to reduce heating) is shrunk. The ring is heated (150°C.) and pressed onto a shoulder of the rotor body. Mechanically good insulation under the retainer ring is necessary, and the required result may be obtained in one of three ways. One method is to cover the windings with insulating channels of laminated phenolic cloth to enclose the coils. Another method is to line the retainer ring with a tube of laminated insulation. Still another is taping end layers with an extra thickness of mica or glass tape. Figure 85 shows the typical slot section of a turborotor, and Figs. 86 an l 87 show the appearance of the rotor.

CHAPTER VII

CONTROL APPARATUS

One would designate as control any device that modifies or controls an electric circuit, and such a classification would include a great many different objects. Control covers an almost infinite variety of parts and auxiliaries used with electrical equipment, and a comprehensive treatment would perhaps be confusing. Entire factories, or even companies, are organized for producing this line of equipment alone, so important has it become. We shall therefore simplify the subject and purposely omit many details. Most control apparatus performs some function related to

1. Opening or closing of circuits, frequently remotely or automatically.
2. Changing a controlling resistance in a circuit to accomplish speed control or other objectives.
3. Changing connections, such as for reversing, often done by an auxiliary push-button circuit or in response to a relay operation. Most of these operations are done purposely in the course of normal use of the connected equipment, in contrast to circuit breakers, lightning arresters, or fuses, which are mainly for protection from emergencies dangerous to the connected apparatus.

In analyzing the points and problems of insulation in control devices, we may roughly divide the field into three parts: (1) contactors; (2) resistors (fixed and adjustable); (3) auxiliaries (push buttons, and relays).

Contactors. DIRECT-CURRENT CONTACTORS.—Since most contactors are mounted on insulating panels made of slate or ebony asbestos board, the mounting studs can also be the main contact studs for the electrical circuits. The mechanical frame on which the moving parts are mounted is electrically part of the moving contact. The stationary contact must then be insulated from the frame in most cases. A molded insulating block, fre-

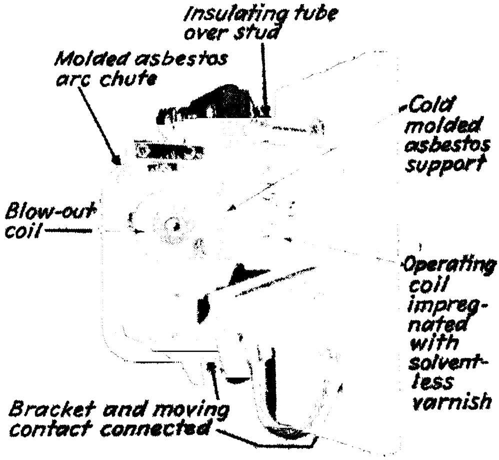


FIG. 88.—Direct-current contactor with arc chute cut away, operating coil above. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

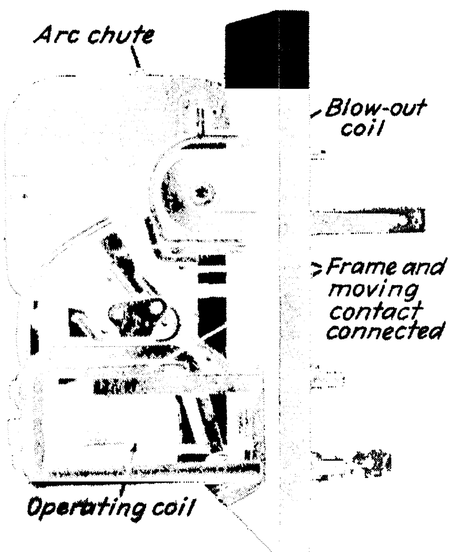


FIG. 89.—Direct-current contactor with half of arc chute removed, operating coil below. (*Courtesy of General Electric Co.*)

quently a cold-molded composition of asbestos and cement, is fastened to the metal frame and supports the stationary contact, the series blowout coil (if used), and the arc chute (Fig. 88). The arc chute is made of similar cold-molded composition, which must be so compounded that good heat shock is obtained and copper deposits from arcs will not collect on the surface. Arc chutes are generally hinged so that they can be easily swung up or down to allow examination and replacement of the contact surfaces. When the main stud of the stationary contact passes through and near the metal support bracket, a laminated phenolic

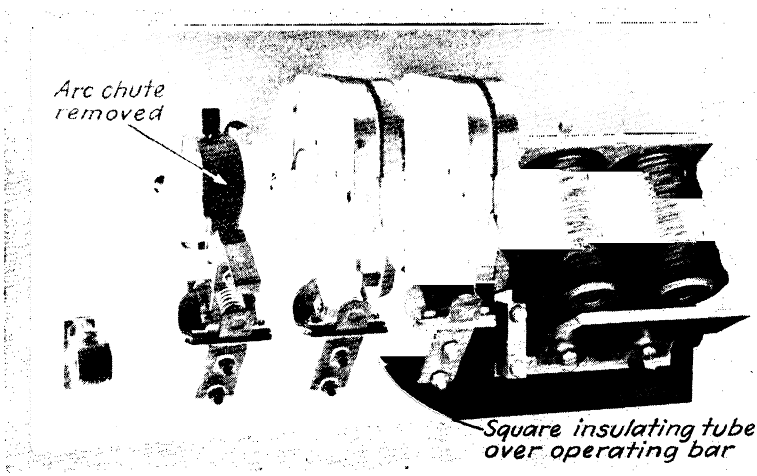


FIG. 90.—Alternating-current contactor, operating coils at one side of contacts. (*Courtesy of General Electric Co.*)

tube is used to encase the bolt. Another arrangement of parts is shown in Fig. 89, in which the magnet coil and the moving parts are below and the stationary contact, arc chute, and blowout coil are fastened directly to the panel.

ALTERNATING-CURRENT CONTACTORS for heavy duty are often designed with the operating magnet at one side, as in Fig. 90. Molded arc chutes similar to direct-current designs enclose the main contacts, which have no blowout coils. The moving contacts are mounted with clamps on an operating bar connected to the magnet armature. Insulation of the square steel bar is obtained by encasing it in a square laminated phenolic tube about which the contact clamps are fastened. Either the same

alternating-current source or a direct-current control circuit may be used on the magnet coil. For alternating current, the core must be laminated to give rapid operation and must also be firmly fastened to prevent objectionable magnet hum. A direct-current coil operating from a copper oxide rectifier is another possible choice. As many contactors as desired can be mounted side by side on the insulating panel and simultaneously operated by the insulated square bar.

Accelerating Relay.—A special direct-current contactor is used as an accelerating relay in motor starting (Fig. 91). It never is called upon to open heavy current and therefore has

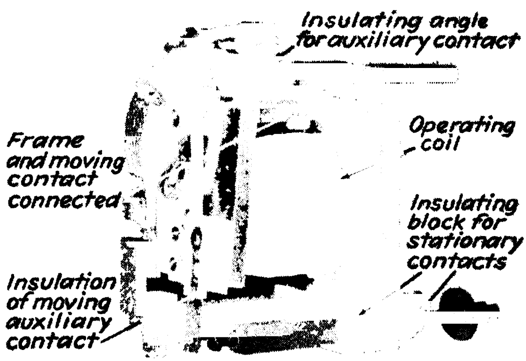


Fig. 91.—Accelerating relay with time delay. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

no arc chute. As normally used, when its coil is energized the contacts are open. When the main-line contactor closes, the coil of the accelerating relay is opened, and a spring starts to close the contacts. By means of a copper tube over the core, the decay of flux is delayed and the relay closing is delayed ½ to 4 sec. as predetermined. When closed, the contacts short-circuit a step of resistance in the motor starter. Several successive relays may be operated in starting a large direct-current motor. Insulating of one stud and the auxiliary circuits is obtained by molded phenolic blocks and angles.

Multipole contactors of small rating (10 amp.) can be obtained to control several connections in one operation. Many combinations can be made from standard parts. Figure 92

shows an assembly with four poles at the bottom normally closed and four poles at the top normally open. The operating solenoid is in the middle and is connected with all poles by crossbars. Any desired combination of "make" and "break" can be arranged from two to eight poles. The base and barrier for the stationary contacts and the connecting bar for the moving contacts are made of cold-molded material mounted on a metal base. To prevent an arc striking the metal base, a sheet of phenolic laminated board is inserted between the molded block and the metal.

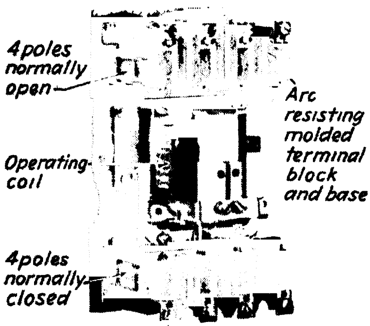


FIG. 92.—Multipole contactor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

DEION STARTERS.—For use in starting small alternating-current motors directly on the line, a contactor employing the Deion-circuit-breaker principle has been developed. The magnet coil and operating plunger are on top. Stationary contacts form an incomplete arch bridged from below by the moving contacts so spaced that an arc formed on opening will travel to the top of the gap and be forced by magnetic action into metal Deion grids and dissipated. The housing containing the contacts and the grids is made of porcelain, a special nonporous body adaptable to forming accurately in configurations such as the recesses and slots for terminals and grids.

Resistors. RESISTANCE TUBES.—Small resistance tubes are used in control, metering, and switching circuits to limit current. They consist of porcelain tubes wound with resistance wire and coated with a vitreous enamel of low melting point and colored usually brown or blue. Metal clamps or wire "pigtails" at the ends form the terminals. Some resistors using heavier wire are wound on grooved or threaded porcelain tubes without external coating. These tubes can be supported mechanically from the terminal clamps or by a bolt passing through the tube.

STRAP RESISTORS are wound with resistance ribbon formed edgewise into a spiral, allowing space for ventilation between convolutions. The core or support comprises a flat steel bar

covered by two mating pieces of heater porcelain, provided with grooves or lugs for holding the ribbon properly spaced. Bar units can be mounted in any desired member in metal frames, as in Fig. 93. The advantages of the edgewise-strap type of resistor are high rating (they can be run red-hot), a constant resistance that does not vary unduly with temperature, compactness, and ability to withstand mechanical shock and vibration. For many applications, they have replaced cast grid resistors altogether.

Grid resistors are usually made of an alloy cast iron in the form of loops or convolutions in the same plane. Typical forms are shown in Fig. 94. The separate grids are assembled into

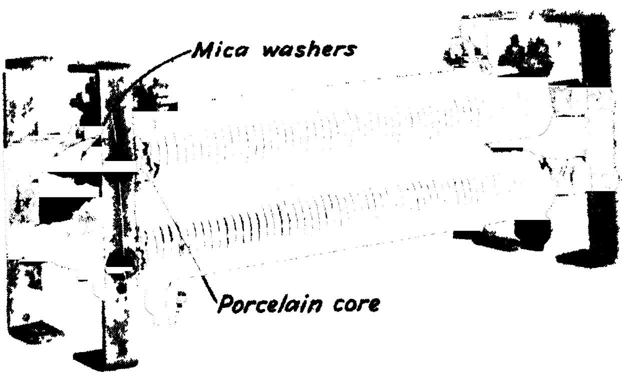


Fig. 93.—Edgewound resistor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

resistors by threading on through-bolts which are covered with mica tubes for insulation. If several grids are to be used in parallel, they are stacked in contact. For a series connection, mica washers are placed over the insulated bolt to separate adjacent grids. End frames of heavy sheet metal are used to support the bolted assembly. If it is necessary to insulate the end frames from the bolts, mica washers can be used for the purpose, as shown in Fig. 94. Great improvement in the toughness of the iron alloy has been made, so that the grids are less fragile; but inherent changes in resistance with temperature and weight of grids compared with other forms are sometimes serious handicaps.

Rheostats may be the faceplate type in which the contact points are arranged in a circle on a panel or the drum type, with

contacts on a cylinder, which is often called a "drum controller." A rheostat is really a combination of resistors with a means for switching sections in or out of the circuit.

A faceplate type for controlling the speed of a wound-rotor induction motor is shown in Fig. 95, without the enclosing case. The contacts, arranged in three sectors of the circle, are bolted

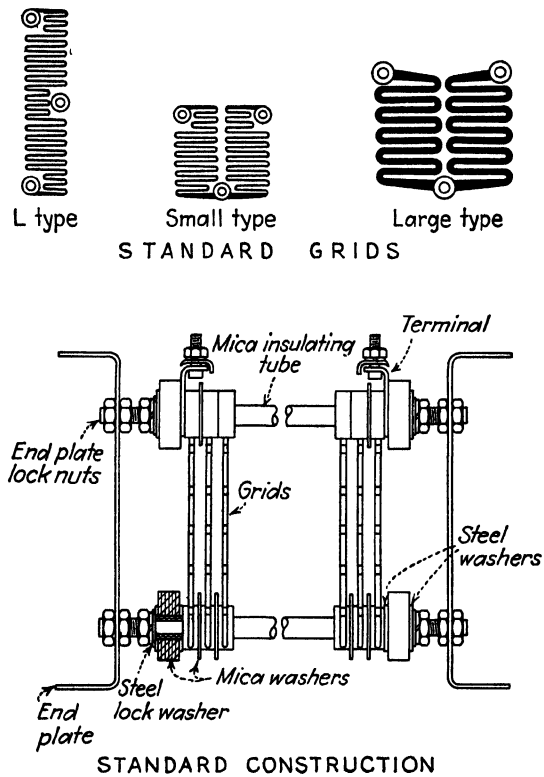


FIG. 94.—Grid resistors. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

through the panel, which may be slate, ebony asbestos, or a molded composition plate. On the rear the contact studs are connected to taps of the resistor units. The circuit is completed by moving contacts on the radial arms rotating on a central shaft. If all three arms are to be connected together as the neutral of a Y-circuit, there need be no insulation at the moving contact; but the arms must be insulated with a bushing from the

shaft. The shaft is operated by hand or by a sprocket and chain driven remotely and must be at ground potential. If the contact arms are to be insulated from each other, a bridging contact may be bolted through an insulating block to the arms. The incoming connection is often made to a solid annular ring fastened to the panel and on which the bridging contact rides. Sprocket-operated shafts usually are further insulated by a circular insu-

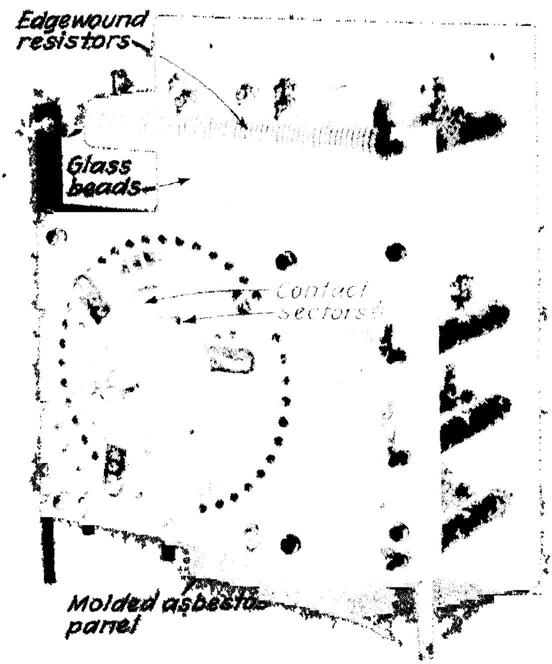


FIG. 95—Speed-control rheostat (*Courtesy of Westinghouse Electric & Manufacturing Co*)

lating plate carrying the sprocket ring. There is then double insulation, from the moving arm to the shaft and from the shaft to the sprocket. Faceplate rheostat mechanisms can be used with grid resistors or any other type as well. Most often, the resistor is near the faceplate, but it may be located at a distance if the problem of cable connections is not too difficult.

Small faceplate rheostats for light duty such as field control of motors are usually self-contained. The plate is often cold-

molded (asbestos composition), and the studs may be molded in place or bolted through. Phenolic plate would not be satisfactory, for the arcing between studs would soon carbonize a path. Resistance coils are connected between studs on the rear, and the assembly is cemented in place and protected with a ceramic cement. If it is necessary to cover all live parts, a metal cover can be fastened to the faceplate with the operating handwheel projecting through it. Another cover over the rear can also be used if needed.

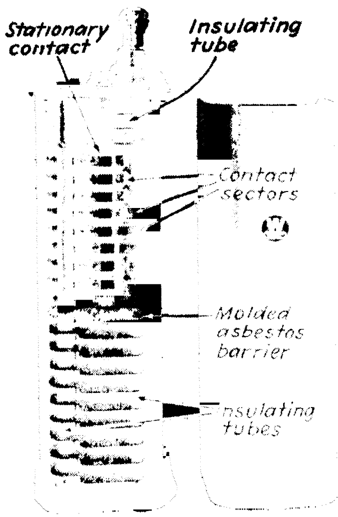


FIG. 96.—Drum controller. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

DRUM CONTROLLERS are familiar in streetcars and cranes. They usually consist of a case in which a vertical shaft rotates to connect segments on the shaft to stationary contacts arranged in a vertical row. The steel shaft is insulated with a rolled phenolic tube to which disks carrying the contact segments are clamped in the correct angular position (Fig. 96). The stationary-contact fingers are clamped to a square bar insulated with square phenolic tubing and ride the sectors as they pass. Each contact and sector then is an individual contactor (Fig. 97) which may change the current of the motor and be subject to arcing.

A stack of arc chutes with blowout coils is provided to cover all contacts in separate chambers, which can be swung aside for inspection and repair of contacts. A piece of sheet steel is placed between adjacent chute sides to aid in blowout.

Auxiliaries. SMALL RELAYS.—In some circuits a light-duty contacting device is required that will close or open a heavier circuit. The studs are mounted on a molded insulation or laminated base. The moving contacts are fastened to a molded insulating plate which moves with the armature of the operating magnet. Both opening and closing contacts can be used.

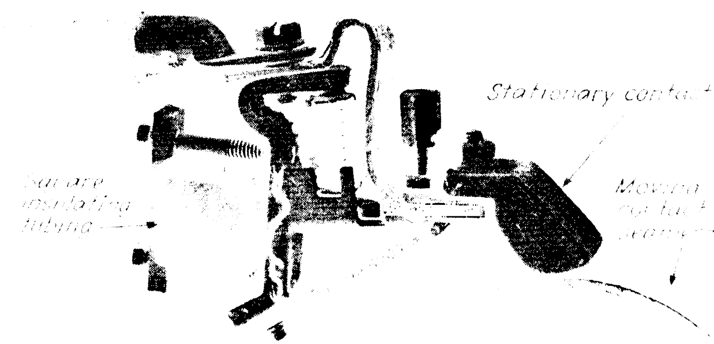


FIG. 97.—Segment and contact of drum controller. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Flexible leads threaded through the moving plate connect terminals to the moving contacts. The armature is magnet closed and spring opened.

THERMAL DEVICES.—A useful overload protective device for motor control is illustrated in Fig. 98, wherein two thermal elements in tandem are shown assembled. Each bimetal passes through a heater carrying line current in each of two phases of a motor, for example. Continued overload in either or both will bend the bimetal strip and push on a molded insulating rod. If the rod moves sufficiently, the end of a toggle snap-action switch moves and snaps auxiliary contacts together to operate any desired protective device. This toggle switch has the

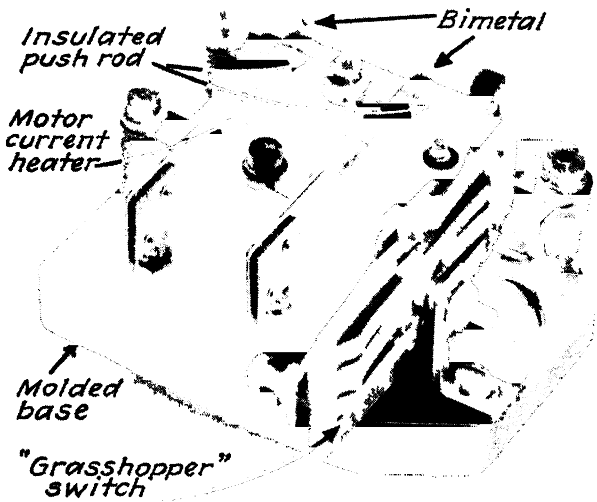


FIG 98 —Tandem overload thermal relay (*Courtesy of Westinghouse Electric & Manufacturing Co*)

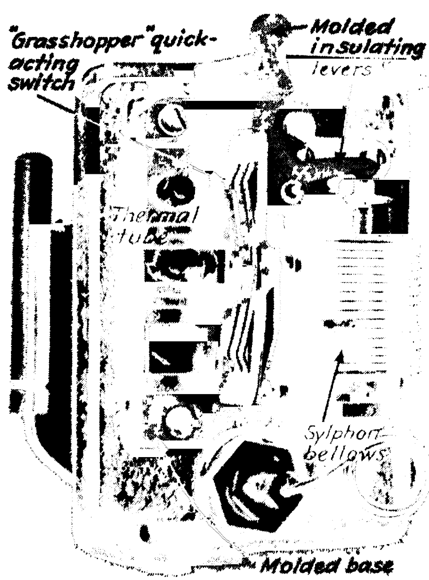


FIG. 99.—Temperature relay. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

descriptive name of "grasshopper" switch, because of its shape and motion. The mechanism is similar to the strip thermostat used in one type of flatiron, except that in the iron the "grasshopper" itself is made of bimetal.

Another type of thermal relay is shown in Fig. 99. This is used to protect bearings, motors, or transformers from overheating. A thermostatic bulb with suitable expanding liquid is placed at the point to be protected, and a tube run to the relay, terminating in a metal bellows. Overheating causes the bellows to move, pushing on a lever which flips the "grasshopper" relay described above.

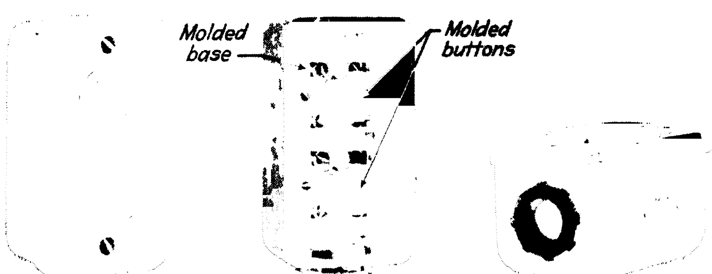


FIG. 100.—Push buttons (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

PUSH BUTTONS are simple but necessary parts of many control systems. A desired action is usually initiated by a push button connected to a relay, contactor, or other device. Several different functions can be accomplished with push buttons. Circuits can be momentarily opened, momentarily closed, both operations on the same button by using double contacts, or the same circuit combinations may be maintained (the button stays in when pushed). The buttons themselves are made of molded phenolic or urea material, usually in colors to identify operations, such as "start," "stop," "slow," "forward," and "reverse." Contacts are assembled on a molded insulation base fastened to a metal case. The cover may be metal or molded material. Typical buttons are shown in Fig. 100.

MAGNET COILS.—So far, little has been said about the magnet coils that operate contactors and relays. They are important enough, however, to give the name "magnet wire" to the sizes

and types of wire used in winding them. Selection of the insulated wire for a coil depends on several factors, such as number of turns, voltage per turn and per layer, space limitations, temperature of operation, moisture, and other atmospheric conditions. There are many types of wire, and each has its proper application, with respect to serviceability and cost.

Enameled wire adds the least to the wire diameter and is adequate where voltage is low, particularly on direct-current where a short-circuited turn does no great harm. It is practically impossible to make enameled wire without occasional defects, such as bare spots or pinholes through the enamel. These defects are lessened with a double-thick coating of enamel, but even this is not perfect. Single cotton over the enamel adds to the thickness but offers increased insulation. Paper-covered enameled wire is thinner than cotton-covered enameled wire, and is a very satisfactory insulation. Organic insulation cannot be used at very high temperatures. A safe limit may be taken as 95 to 100°C. total temperature. Most magnet-coil failures appear to be due to overheating, often because of lack of ventilation inherent in most coils of this type. Glass-covered wire or asbestos will withstand higher operating temperatures, but the limitation in these cases is the impregnants with which they are treated. Neither glass nor asbestos is extensively used in magnet coils. Usually, sufficient temperature margin can be allowed in the design to permit organic insulation to be used.

In moisture resistance, the insulated wires can be listed in order of decreasing merit: enamel, glass fiber, cellulose acetate, silk, Cellophane, paper, cotton, and asbestos.

The choice of wire is further determined by the method of coil winding. There are three common methods, *viz.*, layer wound, random wound, and universal wound. In *layer winding*, the wires are laid side by side in regular order, and when the width of the coil has been traversed a sheet of paper or other thin insulation is wrapped in place before another layer is started. This decreases the possibility of two wires of wide potential difference being in contact and extends the safe use of enameled wire. A supporting spool is required, which may be constructed of a shellacked paper or phenolic paper tube with flanges of similar material. For some applications, fiber will do. A completely molded spool is frequently used. In *random winding*, the wire

is wound on the spool in irregular layers with no extra insulation. This method allows more turns per square inch cross section but requires good wire insulation. A third method, often used in magnet coils, is the *universal* method in which a self-supporting coil of enameled wire is wound on a tubular core with no flanges. The process requires a special machine which weaves cotton yarn in between the turns of wire as it is applied to the coil. The yarn bobbin moves back and forth across the width of the coil very rapidly and practically separates each wire from every other at some point. The yarn holds the turns mechanically and also makes a good absorber for insulating impregnants.

In magnet coils, impregnation is given to improve the insulation by moistureproofing and to increase the heat conduction. Getting the heat out from the interior of a coil is sometimes

TABLE XVII.—MAGNET-COIL DIMENSIONS
(Enameled wire wound with cotton on universal winding machine)

Wire size, American wire gauge	Turns per layer per in. length	Layer-space factor	Layers per in. depth	Depth-space factor	Turns per sq. in.	Cross-section space factor
20	28	0.94	27	0.92	756	0.865
21	31	0.94	30	0.92	930	0.865
22	34	0.94	33	0.92	1,122	0.865
23	39	0.94	38	0.92	1,482	0.865
24	43	0.94	41	0.91	1,763	0.855
25	48	0.94	46	0.91	2,208	0.855
26	54	0.94	52	0.91	2,808	0.855
27	60	0.94	58	0.91	3,480	0.855
28	67	0.94	65	0.91	4,355	0.855
29	75	0.94	72	0.91	5,400	0.855
30	83	0.94	80	0.91	6,640	0.855
31	95	0.94	91	0.91	8,645	0.855
32	104	0.94	100	0.91	10,400	0.855
33	118	0.94	114	0.91	13,452	0.855
34	131	0.94	125	0.90	16,375	0.846
35	148	0.94	139	0.89	20,572	0.837
36	163	0.94	152	0.88	24,776	0.827
37	182	0.94	167	0.87	30,394	0.818
38	200	0.94	183	0.86	36,600	0.808
39	230	0.94	207	0.85	47,610	0.799
40	253	0.94	227	0.84	57,431	0.790

difficult. Thorough impregnation is important and is usually obtained by vacuum and pressure treatment. Melted gums are successfully used for this purpose and have the advantage that no solvent has to find its way to the surface. If careful drying is carried out, varnishes of the clear or asphaltic types may be used. A preferred treatment is impregnation with solventless varnish which eliminates the solvent problem but requires special equipment.

Coil Space.—The foregoing table shows the space taken for turns and layers of universal-wound coils of enameled wire. These figures are practical values based on design procedure for magnet coils. Space for any other kind of insulated wire wound by the same method can be derived if the ratio of insulated cross section of the proposed wire to enameled wire is known.

TABLE XVIII.—INDUSTRIAL CONTROL APPARATUS RECOMMENDED CLEARANCES* BETWEEN UNINSULATED NONARCING PARTS AND TO GROUND

Maximum rated voltage	Minimum clearance distances, in.			
	Through		Across clean dry surface	
	Air	Oil	Air	Oil
150 and above 50	1/8	1/8	1/4	1/4
300	1/4	1/4	3/8	3/8
600	3/8	3/8	3/4	3/4
2,500	1	3/4	2	1
7,000	2	1 1/2	3 1/2	2

* These clearance distances should be increased for dirty or moist conditions.
The clearances listed above agree with adopted N.E.M.A. Standards.

The spacing through air between any uninsulated live or current-carrying parts and the walls of a metal enclosure should be not less than 1/2 in., including fittings for the connection of conduit or armored cable; but if the rigidity of an enclosure is inadequate because of its size, shape, or the material used, a greater spacing is to be provided. A lining or insulating material employed to ensure the required spacing must be not less than 1/32 in. in thickness.

MAGNET WIRES.—Insulated wires used for winding the coils of electromagnetic apparatus such as control magnets, trans-

formers, rotating machines are classed as magnet wires. They may be distinguished from insulated conductors used for switchboards, house wiring, external connections on rotating machines, and power-distribution wires by the degree of insulation. Magnet wires are not insulated for high voltage, and frequently the insulation is untreated as applied. It is not expected that full line voltage of the apparatus in which it is used will be applied to the insulation of the conductor. Where the magnet wire is adjacent to parts at a great difference of potential from the wire, extra insulation must be provided (*e.g.*, slots of motors have slot insulation). Usually, magnet-wire coils are impregnated after winding, partly to hold the wires and chiefly to supply added insulating value. Choice of the type of magnet wire will depend on the space factor desired, impregnating properties, temperature, volts per turn, and cost.

TABLE XIX.—MAGNET WIRE

Type of insulation	N.E.M.A. symbol	Outside diameter #30 B. & S., mils	Outside diameter #20 B. & S., mils	Relative cost #20 B. & S.
Bare		10	32	100
Single enamel	E	10.8	34.1	122
Heavy enamel	HE	11.5	34.8	122
Single silk	S	12		
Enamel single silk	ES	12.8		
Single glass	G	13		
Paper enamel (Jap)	PE	13.4	36.6	169
Paper enamel (rope)	PE		37.6	137
Single cotton	SC	14.5	37.3	145
Enamel single cotton	EC	15.3		
Heavy enamel cotton	HEC	16	39.1	156
Double glass	DG	16.3	39.3	
Single asbestos	A	18	41	570
Double cotton	DC	18.5	41.3	186

MAGNET-WIRE CONSTRUCTION.—Substantially the same methods and machines are used for wrapping wire with cotton, silk, paper, or glass fiber. Cones or bobbins of the material are rotated at high speed (1,000 to 6,000 r.p.m.) around the wire as the wire advances through the center of the spindle. Guides

called "nosepieces" direct the material at the proper angle and maintain tension. The objective is a continuous smooth covering of uniform thickness with no "skips" (bare places). A proper selection of thread sizes and number of threads, or width of paper ribbon, must be calculated to suit the feed and speed of the covering machines. Yarn composed of coarse threads, few in number, will be low in cost but may not cover without occasional gaps ("skips"). Conversely, fine yarn itself costs more but covers the wire well. Cotton, paper, and glass coverings have some points in common, but they also possess several distinctive features of construction which will be set forth.

Cotton Covering.—The terms "single," "double," or "triple cotton covering" refer to the number of separate layers of yarn applied to the wire, successive layers being wound in opposite directions (left- or right-hand wrapping). Cotton coverings may be applied on bare copper wires or over enamel. Single cotton over enamel is a desirable and widely used combination, more than equivalent in insulation and taking less space than double cotton. Double cotton may be better for some coils where a cementing of turns by impregnating compounds is necessary or where the wire is stretched or deformed in winding so drastically that an enamel coating would fail. Enamel is not common on conductors larger than #10 B. & S. or on square or rectangular wires, because of manufacturing difficulties. Double cotton is the usual practice for these wires.

Yarn is a grouping of threads laid parallel. Each thread, called a *single*, may consist of several individual cotton fibers twisted in the familiar thread fashion. We should expect that thread, like wire, would be gauged by its diameter, but this is not the practice. Measurement of diameter of a soft material like cotton by any method except optical would be quite a task. And there might even be considerable doubt about a projected image, since thread has fuzz of an indefinite depth on the surface. The unit of thread size is based on 840 yd. per lb. Number 20 thread is then a size of which it takes 20 × 840 yd. to weigh a pound. The range of thread sizes in yarn used for cotton covering is #20 to #120, the latter requiring 100,800 yd. for a pound.

Although the accepted method of measuring cotton thread size is by length and weight, the diameter must be determined in

some way in calculating space taken by yarn, both along the wire and as thickness added to the wire diameter. A table of nominal diameters is therefore available but must be used with an experience correction factor. Actually, the space taken is 10 to 15 per cent greater than the nominal.

TABLE XX

Thread Number	Nominal Diameter, In.
120	0.00349
100	0.00384
90	0.00403
80	0.00427
60	0.00493
40	0.00603
20	0.00856

From 8 to 24 singles (threads) laid parallel make up the yarn. When yarn is spun around the wire, the threads make one revolution as the wire advances a distance known as the "lead" or "feed." The angle the yarn makes with the axis of the wire is called the angle of "lay" and is dependent on the rate of feed and the diameter of the wire (Fig. 101). For small wires or high rate of feed, the angle of lay must be greater if skips are to be avoided. In covering B. & S. sizes #10 to #24, the lay for a given type of covering machine may be changed from 10 to 50 deg. Typical feeds for cotton covering give 12 to 19 laps, or revolutions, per inch of wire length.

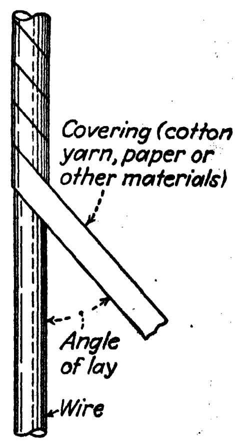


FIG. 101.—Wire covering showing angle of lay.

Paper Covering.—Thin paper in the form of ribbon or tape is applied to magnet wires in a manner similar to that for cotton, except that the angle of lay is different. Two common forms of paper-insulated wire are made, one with a thin paper (Jap or Manila rope paper 0.001 to 0.002 in. thick) applied half-lapped over bare wire with an adhesive. The other is a covering of thin Manila rope paper with butted edges applied with an adhesive over enameled wire. On small wires there is a slight overlap, and on large sizes a slight skip is permissible. The lead for half-lapped paper is usually in the range to give

7½ to 10 turns per inch length; butted covering can be made with a much lower angle of lay, giving 2 turns per inch.

Glass-fiber Covering.—Although glass is treated as a textile fiber, the method of construction and measuring is different from that for cotton. The basic form for electrical uses is an untreated yarn consisting of 102 parallel fibers, each approximately 0.0003 in. in diameter. The unit of measurement is 100 yd. per lb., so that #900 yarn, a common size, has 900 × 100 yards to the pound. The term "yarn" applied to glass signifies the elemental product as it comes from the glass machine and having 102 fibers. In the case of cotton, it means the parallel combination of twisted threads ready to wrap on the wire.

We have stated that, with cotton, threads consisting of twisted fibers are paralleled to make the yarn applied to wire. The process for glass is similar. Fibers are twisted to yield a thread that is paralleled with others for applying on wire. Many twisting combinations are in use. The simplest is formed by twisting a pair of 102 fiber yarns and twisting the pair together with another similar pair. Thus we have four 102-fiber yarns grouped, first by pairs and then by pairing the pairs. The name given to this combination is 2/2, ("two over two"). Another combination is 3/2, which is constructed by twisting together 3 yarns of 102 fibers each and then twisting the triple together with another triple group. The final combination of twisted twists is then a thread, and several of these composite threads (two to six) may be used side by side in covering wire. Threads designated as 2/2, 3/2, 4/2, and 5/2 are in use. A complete specification might be written as 6-2/2 #900, meaning 6 threads constructed on the 2/2 basis of #900 yarn.

The covering operation is essentially the same as in the case of cotton, and the thickness of insulation may be the same or thinner, depending on the glass-yarn construction chosen.

A table, comparing the insulated diameters of several of the magnet wires, using cotton, glass, paper, and enamel in various combinations, is given in Appendix A.

CHAPTER VIII

TRANSFORMERS AND REACTORS

The two essential circuits in a transformer, the electric and the magnetic, have experienced many changes of form. Linkage between the two has been obtained in various ways, sometimes with the iron as the internal or core member, and sometimes with

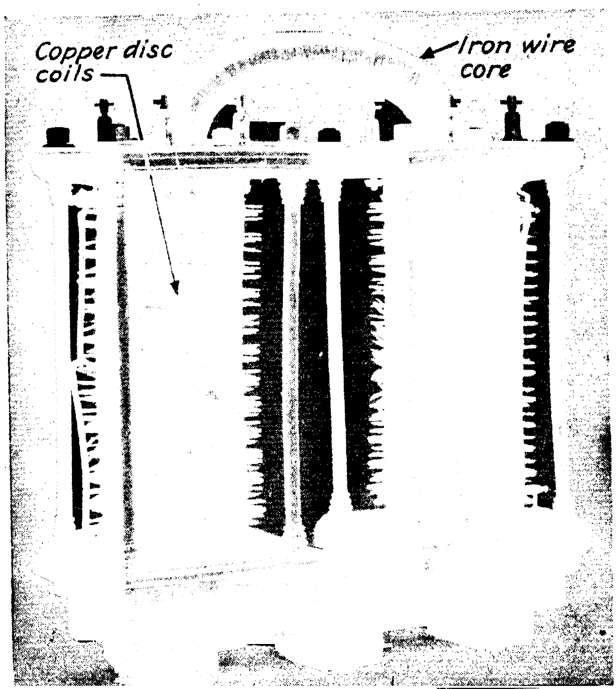


FIG. 102.—Early Gaulard and Gibbs transformer. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

the copper on the inside. Although we now find the iron always in the shape of flat punchings and the conductor in the form of wire or strap, the reverse was true of the original Gaulard and Gibbs transformer. In that device the core was a continuous

loop of iron wire, and the conductors were stacks of copper sheet punchings, connected by external leads soldered to projections on the ring punchings (see Fig. 102).

As far as the relation between core and conductor is concerned, present-day transformers belong to two classes, the shell type and the core type. Briefly, we may say that in the shell type the iron surrounds the coils and in the core type the coils surround the iron. A further description will help to clarify this distinction, a geometric difference that determines the construction of coils and their insulation.

SHELL TYPE

Coils are usually hollow rectangles, like a letter O with straight sides (Fig. 103). The core is stacked in two or more sections

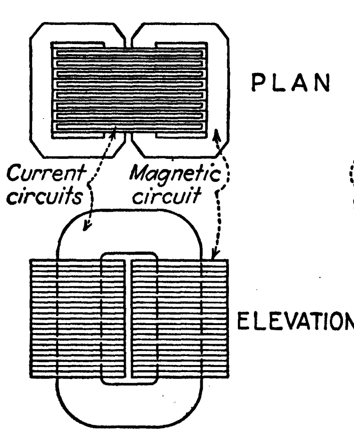


FIG. 103.—Shell-type transformer. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

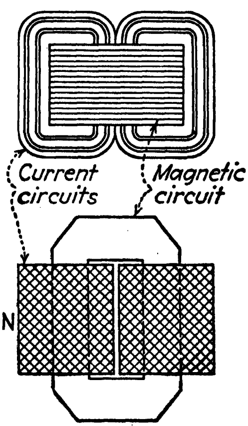


FIG. 104.—Core-type transformer. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

around the coil sides and in the simple form resembles a figure 8 made of straight lines. The flat side of the coils is in a plane perpendicular to the plane of the core laminations. In large power transformers the coils usually stand vertical, and the laminations are horizontal. The reverse is often true in small distribution transformers.

CORE TYPE

An interchange of geometric shape between copper and iron gives us a core-type unit (Fig. 104). Here the coils (usually

with the plane of turns horizontal) are assembled over the legs of the iron core (the laminations usually vertical). The core in this case is essentially a vertical rectangle. One side, usually the top member, must be added after the coils are in place.

Many modern cores are not so simple as the elemental shell- and core-type forms. Added parallel magnetic circuits are used, for example, the cruciform core, applicable to either fundamental type (Figs. 105, 106). Coils then take on a circular shape instead of rectangular. Usually, the added core legs or sections are not so

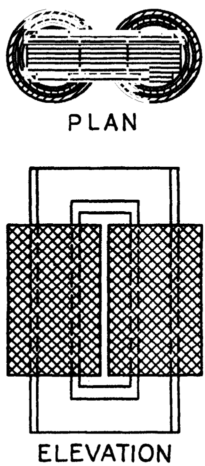


Fig. 105.—Cruciform-core type. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

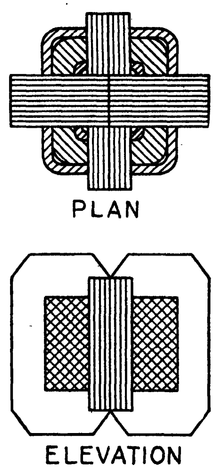


Fig. 106.—Distributed-shell type. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

large as the main sections. Modifications of core shape to provide wider sections outside the coils are used to reduce the magnetic density and iron loss. In this way, therefore, the section through the coils can be a minimum and the mean length of turn of coils kept to an economical value. The whole relation of copper to iron is dependent on two factors: losses and material. A balanced design is sought in each case, taking into account iron loss, copper loss, weight (and cost) of iron, weight (and cost) of copper. A large core will reduce iron losses, and iron is a cheaper material than copper, but the length of copper needed to encircle the core is thereby increased and what is gained in iron loss is lost in cost of copper. Conversely, a "slim" core will reduce the length of

turn, but the core loss and exciting current will be increased. In some designs the operating characteristics such as core loss, exciting current, reactance, and regulation are paramount. In others a minimum of material, space, and first cost are the determining factors.

So far we have considered only single-phase transformers. The same general principles apply to three-phase units. In the conventional shell type, the coils are built into the "windows" of the core. In the three-phase core form, the core is built into the "windows" of the coils. Power transformers, as assembled, give the following impression: Viewed in elevation, the shell type appears to be mostly a stack of horizontal iron sheets, with a little of the coils projecting top and bottom. The core type appears as a column of coils with the iron projecting top and bottom. If these characteristics are remembered, it will not be difficult to recognize the two types.

Selection of Core.—At one time there were distinct opinions on the merits of the two types of transformer construction. There was a definite preference for shell or core types, sometimes based on the designer's or customer's whim, and sometimes on the limitations of manufacturing technique. Now, however, both forms occur in almost all voltage and rating classifications. The choice depends on the objectives and intended conditions of service.

For example, it might be argued that a circular coil, frequently associated with a core-type form, is the better geometric shape for resistance to short-circuit forces. But the design of shell-type coils and their bracing has been advanced to meet the problem.

Some of the points influencing a selection of the best type are listed below.

ECONOMICAL USE OF MATERIALS.—The shell form inherently gives a short mean length of turn in the iron circuit, whereas the core form has a short copper turn. A balanced design favors a greater volume of the material having the shorter path. This is the best method of conforming with the criterion that the maximum output of a transformer is obtained when *copper area* × *iron area* is a maximum for any chosen conditions. In the shell type any increase in coil cross section caused by the demand for more insulation is a disadvantage. On the other hand, an increase in area of core-type coils to give more insulation for

higher voltages has less detrimental effect on the optimum product of the areas mentioned above. This all leads to the generalization that small- and moderate-sized high-voltage transformers should usually be made core type. It also follows that low-voltage large-capacity transformers should be shell type. Exceptions to both rules are common, however.

Coil Winding.—When high current rating calls for heavy conductors or multiple strands, there are frequently advantages in favor of coil shapes that are most adaptable to shell-type cores. The positions of leads and taps may be a factor that enters into the decision. Circular coils for core-type construction are usually easier to wind and insulate.

Bracing.—Protection of the assembled windings against movement or collapse under short circuit is achieved in the two types by quite different methods. If the space factor of the coils is poor (because of the large volume of insulating parts and oil space), the bracing of coils becomes more difficult, for insulation is not rigid but "mushy." It is easier to clamp a piece of wood than a piece of corrugated cardboard. Shell-type windings are more difficult to clamp and brace than round coils for core-type forms. Forces on coils will be discussed later.

Ventilation.—Adequate movement of oil to remove heat is necessary. The general shape of core and windings must be chosen with this in mind. Shell-type coils permit a different and sometimes better arrangement of ducts through the winding.

Repairs.—Without doubt, the core-type winding is easier to take apart for replacement of coils. The top section of the core is removed, and the coils can then be slipped off. In the shell type the iron must be completely unstacked before the coils can be removed.

Summary.—A most thorough study of all conditions should be made before a decision is reached as between core and shell types. Often the answer is not apparent until both designs have been calculated and compared.

COIL FORMS

We have discussed the core forms and their assembled relation to coils. The coils themselves may be made in different ways, each for a definite reason. Generally speaking, coils can be

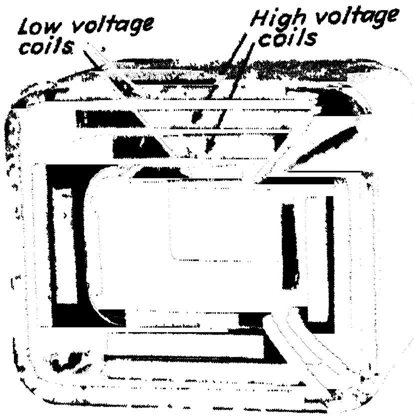


FIG. 107.—Concentric rectangular coils for shell-type distribution transformer. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

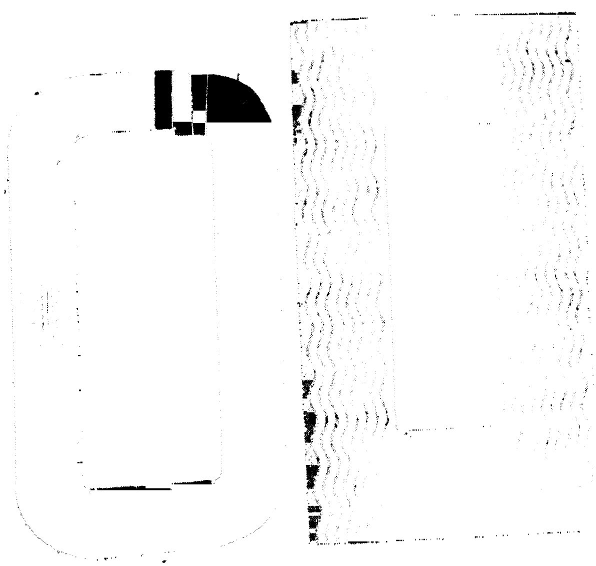


FIG. 108.—Interleaved pancake coil and wavy spacer for shell-type power transformer. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

arranged in two ways, concentrically and interleaved. These terms are almost self-descriptive. In the concentric arrangement, separate coils, particularly the primary and secondary groups, are of different diameter and one fits inside the other (Fig. 107). Windings are thus built up radially, although the shape does not have to be circular. Rectangular coils can be similarly "nested" to give the concentric form. The interleaved construction is made up of a stack of flat or pancake coils, possibly only one or a few conductors thick (Fig. 108). When applied to a shell core, the sections stand vertically, and on a core type they are piled horizontally. Interleaved coils can also be circular or rectangular in outline. A coil only a few turns thick (a thin flat spiral) for core-type construction is usually called a "disk coil"; for the shell type, such a coil is called a "pancake coil."

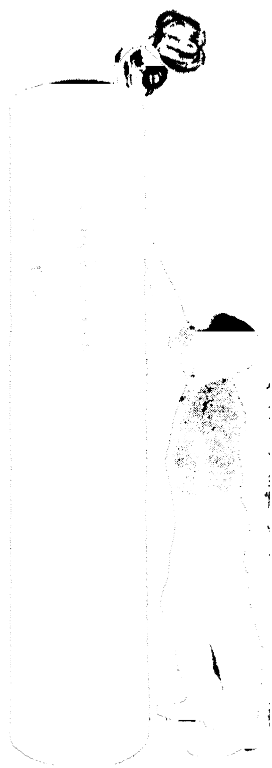


FIG. 109.—Tubular low-voltage coil of 800,000-volt testing transformer. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

In general, it is common for the concentric form to be used in core-type construction and the interleaved in shell types. But this is not always true. For some core-type units, the interleaved winding is preferred, and concentric windings (rectangular) are common in small shell-type transformers (Fig. 107). So much for a brief description. Now let us observe more of the details of coil construction.

Concentric Windings.—In the circular form of winding, all the individual coils may be tubular in form, *i.e.*, wound with a relatively large number of turns per layer and few layers. On the other hand, the low-voltage coils may be tubular in form (Fig. 109), and the high-voltage group built up of a number of disk coils assembled side by side (Fig. 110). The disk coils are

formed with relatively few turns per layer and a large number of layers.

The tubular coils on the larger sizes of transformers have a tendency to become relatively thin radially and long in the axial direction. This does not make a strong mechanical structure, particularly with rectangular coils, and this condition to some

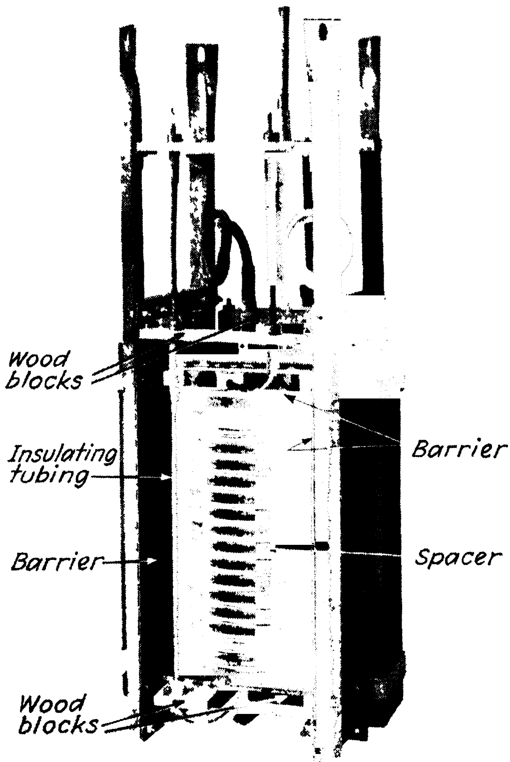


FIG. 110.—Distribution transformer with section-disk high-voltage coils for 39,600/44,000 to 2,400/4,160 volts. (*Courtesy of General Electric Co.*)

degree works against their extended use. With coils of this type, it is difficult to take care of heavy conductors, particularly where the leads issue at the ends of the windings. For the smaller transformers, the concentric form of coil has many advantages and is extensively used, mainly in distribution transformers. The disk form of coil is used chiefly in the high-voltage winding of core-type units.

Interleaved Windings.—Interleaved windings may be used either with the core or with the shell type of construction. As a matter of fact, however, practically all the larger shell-type transformers use this winding, but relatively few of the core type do. The individual coils of the interleaved windings are sometimes called "section-wound" or "pancake" coils (see Fig. 108).

Pancake coils are usually wound with square or rectangular conductors. Sections may be wound with one, two, or more

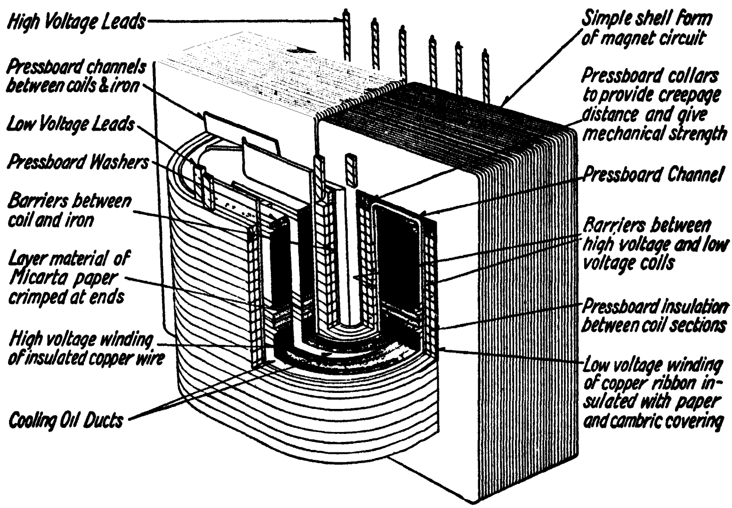


FIG. 111.—Shell-type distribution-transformer. Concentric rectangular coils. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

wires in parallel, depending upon the current capacity desired. They can be wound in either circular or rectangular form, but the latter is the common construction. A coil may consist of one section or two sections assembled together. When the conductors are of a reasonably large cross section, there is no trouble in winding coils that are mechanically strong and rigid. Small coils do not need great strength and can therefore be wound with round wire. For the smaller coils the conductors are generally of such a width as to give a thickness of coil section of approximately $\frac{3}{16}$ to $\frac{1}{4}$ in. and for the large sizes a thickness of $\frac{3}{10}$ to $\frac{3}{8}$ in. If the conductors are not wider than $\frac{3}{8}$ in., the eddy current loss is held within reasonable limits.

The choice of coil construction and assembly is frequently determined by the type of service the transformer is intended to

render. Two common types of transformer are recognized, *viz.*, distribution and power. We may assume distribution transformers to be limited to capacities below 500 kva. and/or voltages below 15,000.

DISTRIBUTION TRANSFORMERS

For small ratings (up to 100 kva.) the concentric arrangement of coils and a rectangular shape are common (Fig. 111). Tubular

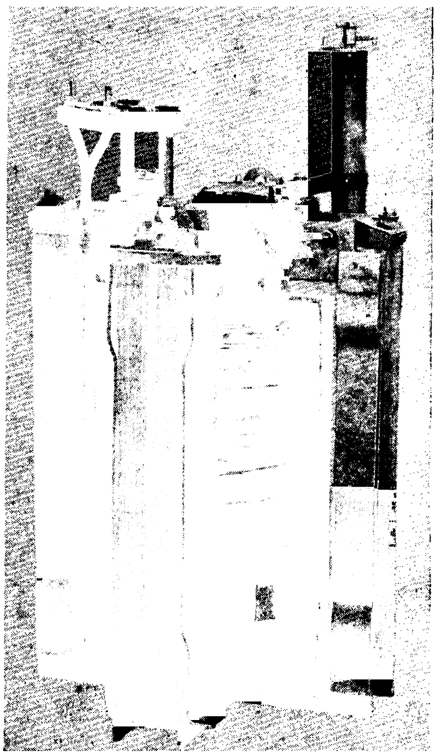


FIG. 112.—Distribution transformer, 25 kva., 6,600/11,400 to 2,300 volts. Shell-type disk coils. (*Courtesy of General Electric Co.*)

and disk coils appear in many designs of larger rating, but exceptions to these rules are so prevalent that no rigid principle can be stated (Fig. 112). Manufacturing practices, designers' preferences, and even customers' desires may determine the choice. All that can be accomplished here is to describe the type forms so that they can be recognized when seen.

Coils for distribution transformers are wound on insulating tubes of pressboard or laminated resin. The tubes may be either round or rectangular, as required. In the latter case the tubes are wound on a round mandrel and formed hot to the desired shape on another mandrel. Barriers of similar shape are placed usually between low- and high-voltage coils to prevent a failure in the high-voltage winding from contact with the low-voltage circuit.

The individual coils, after having been wound on the insulating tubes or forms, are assembled with circulating ducts for oil between coils. These ducts may be either radial or concentric, or both, and are formed by appropriate spacers of pressboard, wood, or other insulation. Ordinarily the high-voltage coils are assembled between the low-voltage units to obtain optimum flux linkage. This increases the problem of insulating, however. High-voltage windings are again divided frequently into sections to eliminate a high voltage between layers. The high-voltage conductors in small distribution transformers are commonly single-cotton-covered enameled wire or paper-covered enameled wire of round section. The wires are wound in layers with paper between layers, which is crimped over the end to form a mechanical barrier. This prevents the end wires from slipping down to the layer below and provides a creepage separation between layers. Low-voltage windings are frequently of larger copper, usually paper and cloth-taped strap with cloth or pressboard between layers.

The transformer, as assembled, is a "raw" unit; *i.e.*, the insulation is for the most part untreated cotton, paper, or pressboard, except for the laminated coil forms. A thorough drying in vacuum and impregnation is therefore required. The impregnation, under vacuum, may be with compound, varnish, or transformer oil only. The object of the first two is the elimination of air pockets and better conduction of heat to the surface; but, for many designs, oil alone is satisfactory and eliminates the possibility of any soluble material contaminating the oil.

POWER TRANSFORMERS

Core Type.—Practically all the types of windings described appear in power-transformer design. For moderate voltages, the high-voltage coils are generally tubular for a core-type core;

but at higher voltages the high-voltage coils are thin disk-shaped, stacked one on top of the other (Fig. 113). They may be wound either in layers with round wire or in sections with rectangular wire, depending upon voltage and capacity (Fig. 114). The thin shape is conducive to good cooling and prevents internal hot

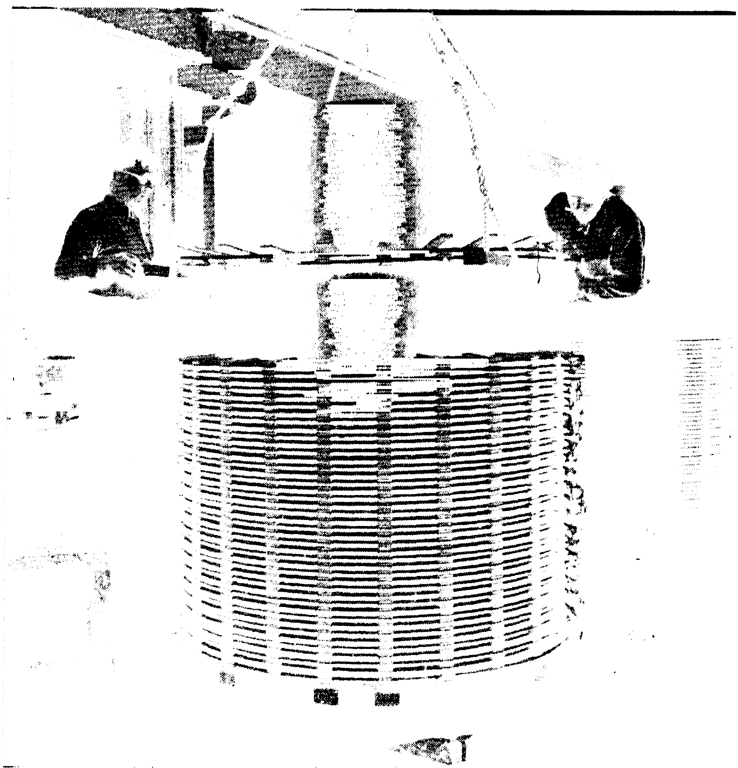


FIG. 113.—Assembling disk coils for a power transformer. (*Courtesy of General Electric Co.*)

spots. These coils are dried and dipped in varnish, which strengthens the insulation mechanically.

Insulating barriers between high and low coils are made of laminated phenolic resin. Coils and barriers are assembled over cruciform core legs and clamped in place by steel end plates insulated with rings of laminated insulation. This gives a rigid construction capable of withstanding short-circuit stresses.

With interleaved core-type windings, high and low coils are separated by pressboard rings of approximately the same inside and outside diameters as the coils. The rings have radial ventilating spacers to separate coils and provide oil circulation.

Shell Type.—In shell-form power transformers, the coils are usually single sections, with square or rectangular conductors.

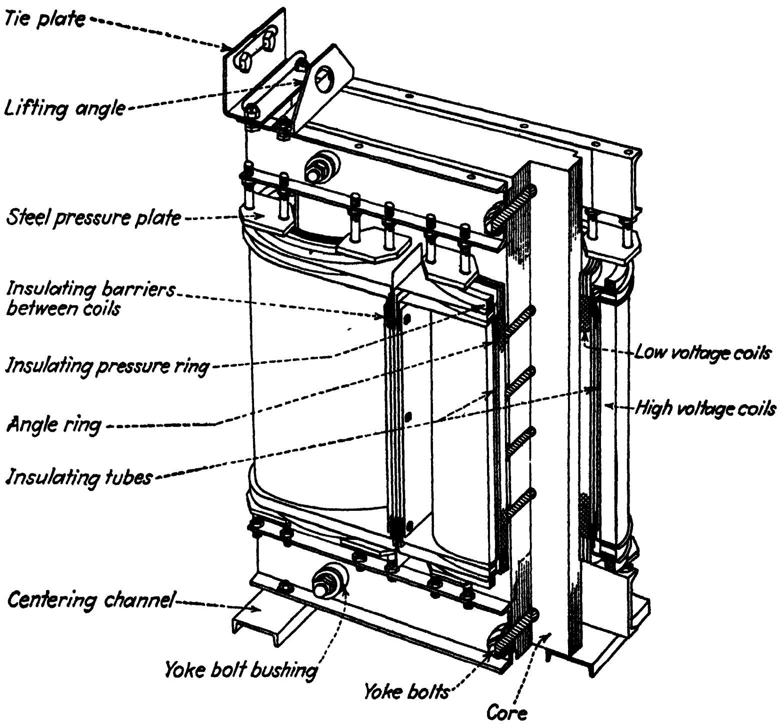


FIG. 114.—Cutaway view of core-type power transformer. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The wound coils are clamped and pressed to size and held to shape during drying and varnishing. The varnishing is done in several cycles until a good finish is obtained—often five times. Ventilating ducts are placed on one or both sides of each coil. One method of constructing these ducts in shell-type construction where the coils stand vertically is the "wavy" spacer section shown in Fig. 108. The wave is to prevent hot spots which might occur if the spacer strips covered a few turns for their whole length.

Instead of wavy spacers, short strips or "buttons" of pressboard cemented to flat sheets can be used (see Fig. 116).

The arrangement of coils and connections is important in minimizing the voltage stresses between adjacent parts. Coil groups are insulated with pressboard barriers and the separate

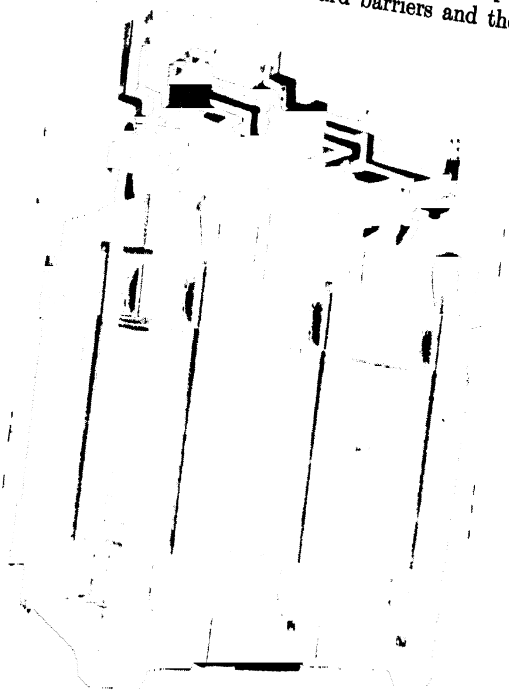


FIG. 115.—Shell-type power transformer with "box" insulation. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

groups assembled for a complete transformer winding. This type of insulation is known as the "box type." The coils themselves are not visible (Fig. 115). The shell core is built around the "boxed" coils. The parts of this "boxing" are sheets, wavy strips, angles, and channels of pressboard cut to proper shape and fastened together with tape and twine.

End Turns.—For high-voltage transformers, extra insulation must be added on the turns nearest the high-voltage terminals

as protection against incoming surges (Fig. 117). It is secured in a layer-wound concentric coil by placing heavy insulation between layers and spacing adjacent end turns by winding cord

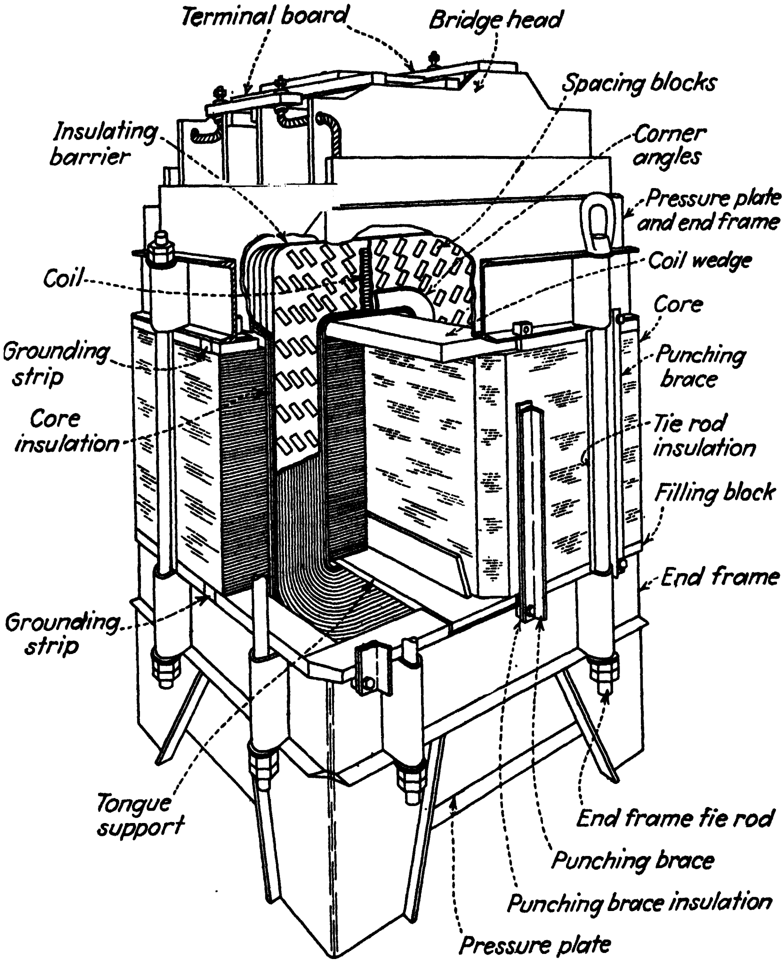


FIG. 116.—Cutaway view of shell-type power transformer. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

between them, the cord being wound with the wire. The extra insulation for pancake interleaved coils is secured by wrapping additional sleeves of paper and cloth around the conductors and by thick strips of insulation between layers.

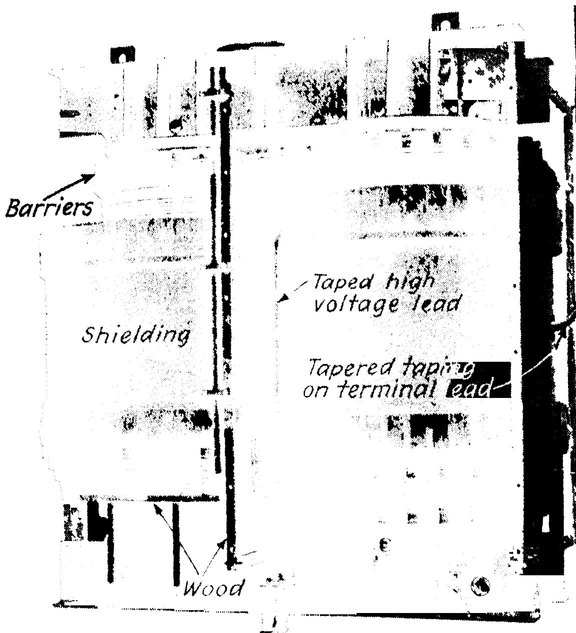


FIG. 117.—Core-type power transformer, 55,000 kva., 287,500 to 16,320 volts. (*Courtesy of General Electric Co.*)

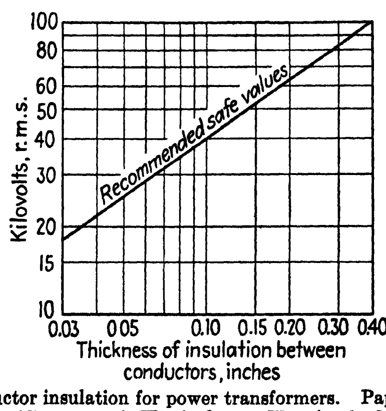


FIG. 118.—Conductor insulation for power transformers. Paper in varnished or oil-treated coils. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

In calculating insulation for a given transformer design, several factors must be coordinated. First, the conductor or turn insulation must be determined, and curves such as that in Fig. 118 may be used as a guide for high-voltage units. Creepage distances

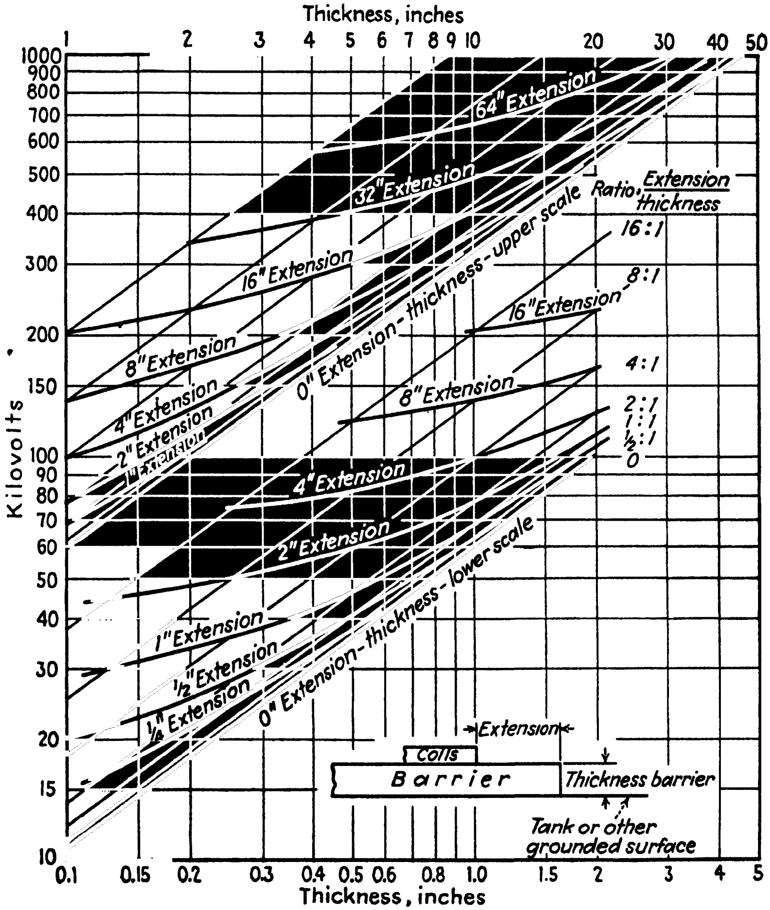


FIG. 119. -Creepage strength of transformer insulation in oil. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

over the surface of insulation between a terminal or conductor and a grounded part such as the core or tank are based on such data as are shown in Fig. 119. For example, if, for adequate puncture strength, a barrier 1 in. thick is required and the distance from coils to ground over the surface (termed "exten-

sion") is 8 in., failure over the surface may be expected at 138 kv. Or assume that a barrier 0.5 in. thick is used and a creepage breakdown of 60 kv. is desired; then the coordinate lines of Fig. 119 meet on the curve marked "2-in. extension." Additional strength against creepage is often given by angle-shaped barriers interleaved at the edges of flat pieces. If the conductor is partly enclosed by such an angle barrier, the creepage voltage is greatly

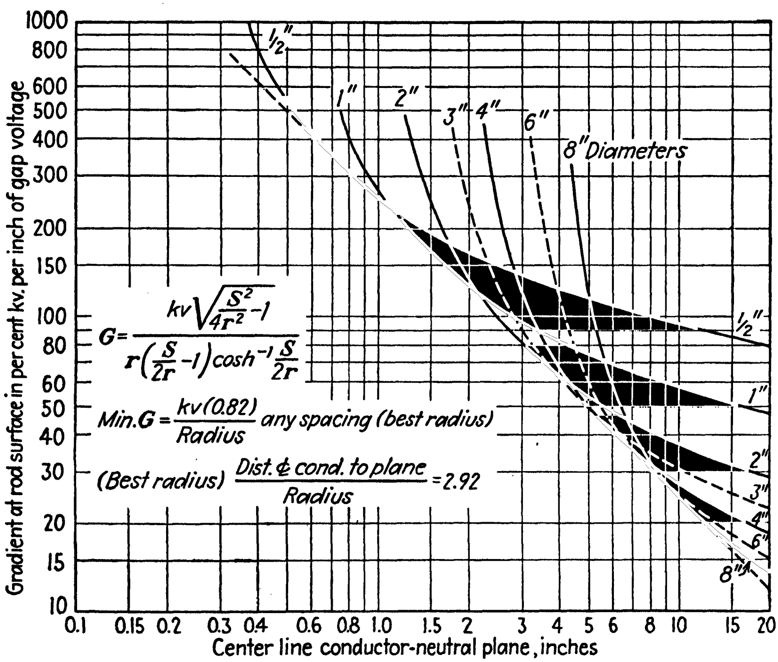


FIG. 120.—Surface gradient for long rod surface to neutral plane for any radius and spacing. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

increased. The angle should be close to the conductor where the gradient is highest and not separated by a considerable oil space.

The puncture strength of a given distance through oil between metal electrodes can be ascertained from curves such as are shown in Appendix A. For large spacings, a much higher strength can be obtained by imposing layers of pressboard to break up the oil space into small layers or sections. For example, a ¼-in. oil space bounded by layers of pressboard covering the electrodes will withstand approximately 50,000 volts, and a number of similar oil and pressboard layers in series will give

substantially a linear increase in breakdown. Two ¼-in. layers of this arrangement have a higher puncture than one ½-in. layer.[1] A design balance must therefore be worked out to find out whether or not economy of spacing is worth the added cost of constructing the barrier with small subdivisions.

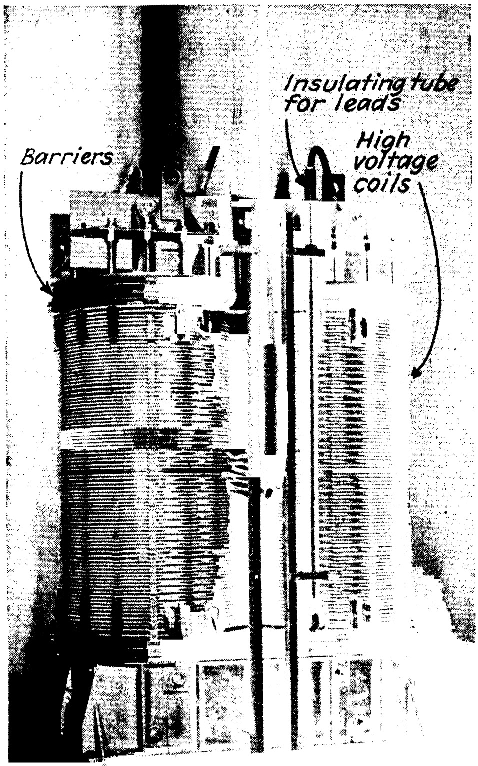


FIG. 121.—Concentric winding, continuous disk, core-type power transformer, 10,833 kva., 37,800/65,415Y to 12,000 volts. (*Courtesy of General Electric Co.*)

Still another problem is the insulation of high-voltage terminal leads emerging from the winding. A starting point for solution of this problem is the calculation of surface gradients. If the gradient at the surface of a certain selected conductor size is greater than the rupture gradient of the oil (if the conductor is bare) or of the taping over the terminal, it becomes necessary to select a larger diameter conductor. From Fig. 120 we may

[1] Westinghouse data.

show a sample estimate. On the assumption of a 1-in. diameter conductor, spaced 5 in. from center line to ground (4½-in. insulating gap) and at a voltage of 127 kv. to ground, the curve shows 74 per cent of the gap voltage, or 94 kv. per in. gradient at the conductor surface. From the known rupture gradients of materials used the designer would then decide whether to apply several layers of tape capable of withstanding the gradient or select a larger bare conductor.

OTHER TRANSFORMERS

Much space would be required to describe adequately the detailed insulating constructions used by the various manu-

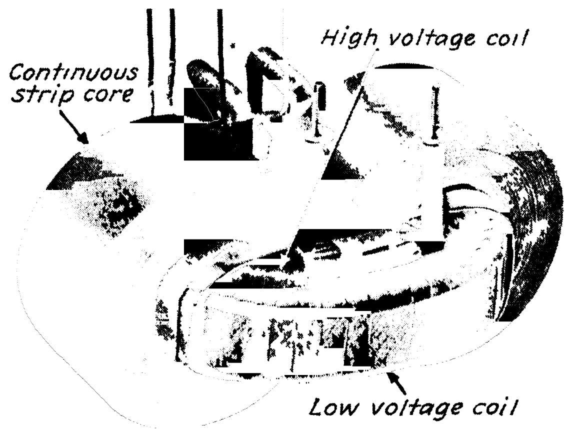


FIG. 122.—Wound-core distribution transformer, 1.5 kva., 2,400/4,160Y to 120/240 volts. (*Courtesy of General Electric Co.*)

facturers of transformers. We have limited our discussion to distribution and power transformers, leaving out the many other varieties such as constant current, air blast, luminous tube, potential, current, and others. Even in one group, distribution transformers, as made by one manufacturer, the winding procedure even of concentric coils takes on different forms as ratings and voltages are changed. We still can recognize, however, the elemental forms such as disk coils, tubular or helix coils, and others.

An interesting winding, called "continuous disk," has the effect of separate circular disk coils as far as spacing and oil flow go, but

there is no break in the conductors. The same strands are carried from one disk to the next, eliminating connections between coils (Fig. 121).

Another form that merits mention is incidental to the development of a new type of core, called "Spirakore." Continuous strip silicon steel is wound like a roll of tape and welded at the finish. The magnetic advantages are important and justify special machines for winding the core around the assembled coils (see Fig. 122). The high-voltage coil is between an inner and outer section of the low-voltage winding, high-low insulation being laminated Bakelite cylinders or a built-up mica pad. The coils are wrapped with heavy paper where the core is applied. Simplicity, light weight, and low cost are claimed for this design.

FORCES ON COILS

In our discussion of cores and coils, we have noted the need for adequate bracing against the mechanical effects of the strong magnetic fields set up by short-circuit currents. An external fault will subject many portions of the windings to stresses, which in some cases balance. An internal failure of some part of the coils may set up unbalanced forces which will cause damage far beyond the one failure point. It has already been stated that the choice of coil form and arrangement often depends on the mechanical rigidity and strength required. A further survey of the possible forces in transformers will make clear the reasons for the geometry of transformer construction.

We may start our analysis with the two well-known fundamental conceptions: Conductors carrying current in the *same* direction *attract* each other. Conductors carrying current in *opposite* directions *repel* each other. Let us consider a simple coil of several turns. Since the current is in the same direction in all turns, there is a pulling-together action between successive turns and a tendency for the coil to contract. But at the same time the currents on diametrically opposite elements of a coil are in opposite directions and have a tendency to repel each other. A long, narrow, rectangular coil under short circuit would therefore tend to bulge toward a circular shape.

Force Action between Coils in a Transformer Winding.—When the primary and secondary coils of a transformer winding are assembled, the currents in those two elements are opposite in

direction. The main force action between them, therefore, will be one of repulsion at all points. Also, one side of a primary coil will attract the opposite side of an adjacent secondary unit. Since the opposite sides of the same coil repel each other, these two forces are practically balanced and are negligible compared with those tending to force apart adjacent primary and secondary units of the winding.

Under short-circuit conditions, these forces of repulsion depend upon several factors, chief among which are frequency, size, voltage, and the amount of reactance in the circuit. The conditions that would give the maximum force action would be a large

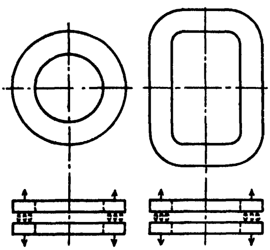


FIG. 123.—Forces between flat interleaved coils, electrical centers identical. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

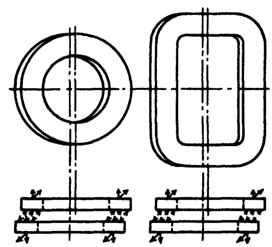


FIG. 124.—Forces between flat interleaved coils, electrical centers displaced. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

transformer, operated on a circuit of low frequency, of moderate voltage and low impedance, and fed from a powerhouse of large rating compared with the size of the transformer. The relative positions of the electrical centers of the primary and secondary coils have a bearing on the distorting effect of the repulsive forces.

The short-circuit stresses can be calculated with a reasonable degree of accuracy, so that the mechanical sufficiency of any design can be determined when the necessary information is available. The following analysis of the various forms of the core and shell forms of transformers will show that the problems of taking care of the short-circuit stresses differ.

Force Action between Flat Interleaved Coils.—For flat primary and secondary coils, having the same over-all dimensions and identical electrical centers, the forces act in the direction shown in Fig. 123. In this case the repelling forces are all at right angles to the plane of the coils. When the electrical centers are sepa-

rated, however, there is a component of force parallel to the planes of the coils as well as at right angles to them, as shown in Fig. 124. This component may be quite large and, in some cases, sufficient to damage the coils by driving them apart.

Figure 125 shows the directions in which the forces act between groups of flat primary and secondary coils in which the groups are concentric with reference to one another, but with one group having smaller dimensions than the other. In addition to the repelling forces at right angles to the planes of the coils, there are components parallel to these planes which tend to force the sides of the smaller coils inward and the sides of the larger coils outward. With a large transformer these forces may be sufficient to seriously damage the windings; and, for this reason, the coils should be made to conform as nearly as possible to the arrangement shown in Fig. 123.

During a short circuit the repelling forces at right angles to the surfaces of the groups of primary and secondary coils in shell- and interleaved core-form transformers may be a few pounds or several thousand pounds, depending upon conditions already stated. With shell-form transformers, the parts of the coils within the magnetic circuit are held so that movement cannot take place, the ends outside the core are braced by wedges driven between the coils, and an extension of the end frame is used as a pressure plate. In interleaved core-form transformers, the coils are braced by heavy insulating rings backed by steel pressure plates which transmit the stress through the end frames into the core itself.

Force Action between Concentric Tubular Coils.—With concentrically arranged tubular windings, whose electrical centers are in the same plane, the forces are at right angles to the axis or center line of the windings, as shown in Fig. 126. This stress is not a serious problem, even for large sizes, when circular coils are used. The outer coil resists the forces through tension in the copper of the winding. Mechanical failure can take place only when the copper itself is stressed beyond the elastic limit. In practical designs the forces are not of sufficient magnitude to make this a factor. The inner coil is subjected to a radial compressive force which it resists as a continuous arch. The inner coil is usually round or assembled on a tube of insulating material which braces it and also serves as insulation to the core. With

concentric rectangular coils the stress may be great enough to cause the outer coil to bulge out and tend to take a circular form. This type of winding is used only on small ratings where the mechanical forces are not of sufficient magnitude to be a problem.

When the electrical centers of concentrically arranged coils are not in the same plane axially, a mechanical force component is produced parallel to the axis or center line of the coils (Fig. 127).

The magnitude of the force depends on the distance between the two windings and on the amount of the displacement. This force is always less than the radial forces between the coils, but it is more of a problem to the designer. Since each coil acts as a

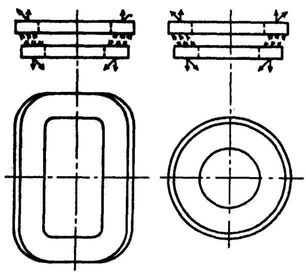


FIG. 125.—Forces between flat concentric coils of different dimensions. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

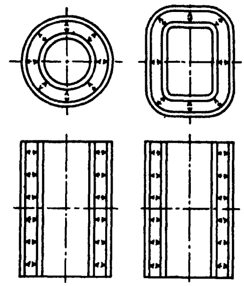


FIG. 126.—Forces between tubular concentric coils with electrical centers in line. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

unit, there is no internal strength factor in the coils that resists the force. The problem of bracing against it is simply and effectively solved by converting the magnetic core into a large tie rod. At each end of the coils on both sides of the core is bolted a steel channel. On the ends of the core column a heavy ring of laminated resin board is placed. Four steel pressure plates at each end transmit the stress from the insulating collar to the end frames by means of adjustable jackscrews which run through the flange of the end frame channel and are welded to the pressure plates.

In addition to proper bracing, transformers are designed to obtain minimum vertical displacement of the high- and low-voltage center lines. With modern manufacturing methods in which the coils are pressed to a predetermined dimension and both clamped between the same plates, the manufacturing variation

is reduced to a negligible figure. When there are taps in one winding, an unbalance must result. This displacement can be accurately calculated and where necessary may be reduced by distributing the taps along the column.

When one coil of a transformer with tubular concentrically arranged primary and secondary windings has a greater axial length than the other and the electric centers are in the same plane, the forces act as shown in Fig. 128. In this case, there is a component of force parallel to the axis of coils, which tends to drive the end turns of the longer winding outward and to force

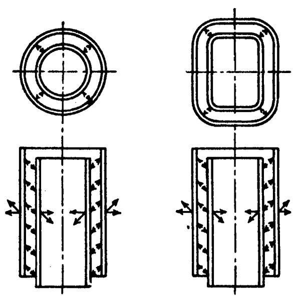


FIG. 127.—Forces between concentric coils when electrical centers are not identical. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

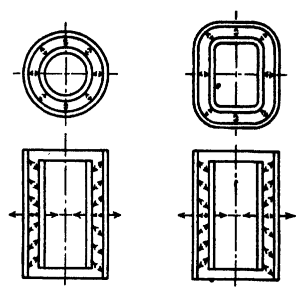


FIG. 128.—Forces on tubular coils having different axial length. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

together the turns of the shorter winding. Considering each winding separately, there is an attractive force between the turns due to the current in all the turns flowing in the same direction. This force is sufficient to overcome the repelling force exerted by the shorter winding on the outer turns of the longer winding, except in case of extreme difference in length. Since maximum economy of space, minimum reactance, and minimum losses are obtained with columns of equal length, there is no incentive to use unequal columns in commercial design.

MECHANICAL BRACING IN RELATION TO VENTILATION

Mechanical bracing as well as ventilation must be taken into consideration in deciding on the arrangements of ventilating spacers between transformer windings. Under certain conditions of short circuit, there may be a tendency in large transformers for the conductors of some of the coils to be forced out of place

and into the ventilating ducts. Displacement is prevented in large interleaved windings, with flat rectangular coils (pancake), by using staggered rows of rectangular block spacers placed diagonally with respect to both the vertical and the horizontal plane, an arrangement that permits good oil circulation. With flat circular coils (disk), the spacers are arranged radially. In both types of design, these spacers give good mechanical support without seriously impeding oil flow or interfering with the transfer of heat from coil to oil. Full benefit is obtained from the temperature head in shell-form transformers, since the spacers are placed vertically. In the concentric-coil form, the relatively narrow disk coils, together with the absence of interleaved insulation, give a construction with a large proportion of winding surface exposed to oil ducts and very little impediment to oil flow. Under ordinary conditions the rate of oil circulation does not exceed about 6 ft. per min., so that the resistance to the flow due to the staggered-block spacers is so small as to have an inappreciable effect upon the temperature. Generally, the difference in oil temperature at the top and bottom of the windings is about 6 to 10°C., irrespective of the type of transformer used.

TRANSFORMER INSULATING MATERIALS

The types of materials used for conductor and coil insulation have been enumerated in previous sections of this chapter. Further the fabrication and properties of insulating materials were covered in Chap. IV, Insulating Materials. It seems useful, nevertheless, to add some further comments about transformer insulation in detail, since the transformer is so inherently insulating in function. Probably in no other common form of electric-power apparatus does insulation represent so great a portion of the composite problem of design.

The important transformer-insulating materials may be grouped as follows:

Inorganic solids.

Organic solids.

Impregnating liquids and compounds.

Inorganic Solids.—The chief inorganic insulators that might be suggested for transformers are asbestos, glass fiber, and porcelain. Thin boards (as for barriers) of either asbestos or porcelain are

not mechanically strong or flexible and are therefore out of the question. With further development, glass-fiber boards may prove to be very useful. One might ask why mica, which is so indispensable for rotating machines, has been left out of consideration. Mica has poor dielectric properties under oil and is rarely used in transformers. Another disadvantage is its high dielectric constant, which increases the problem of voltage gradient where insulation is in series with oil.

Asbestos cannot be called very good insulation, electrically, and its use is confined to air-insulated low-voltage transformers, usually supplemented by better insulation. Porcelain is the only high-quality inorganic insulation in general use for transformer parts; in view of its well-known mechanical limitations, its use is confined to terminal blocks, spacers, and bushings. A possible exception is the use of vitreous-enamel coatings on copper bars for heavy-current low-voltage coils. Glass-fiber-covered conductors are suitable for high-temperature use.

Major dependence must therefore be placed on organic materials, of which many varieties are used.

Organic Solids.—The principal types are

Paper, untreated.
Cloth, untreated.
Treated paper.
Treated cloth.
Synthetic resin products.
Rubber.
Wood.

Untreated paper and cloth have little insulating value above an equivalent thickness of air but when impregnated have excellent properties. Frequently, these products are applied in the untreated form to transformer coils and treated after assembly.

UNTREATED PAPER.—Under this head, we may include thin rope paper (made from hemp fiber) used on wire, frequently over enamel; Kraft paper, used as conductor insulation and layer insulation; cotton paper, such as pressboard (sometimes partly wood pulp), used as coil supports, barriers, and core insulation.

UNTREATED CLOTH is used where a tough flexible material is needed. The thickness range may be 0.005 to 0.017 in. Untreated cloth is used as layer material, as sleeves on round wire, as tape in holding coils or barriers together, in protecting

crossovers between layers, and as folds around taps in the winding.

Treated paper is usually varnish-dipped hemp-fiber paper (rope paper), but occasionally Kraft paper (wood pulp) with a varnish coating is used as insulation between coils and taps where toughness without much flexibility is desired.

Treated Cloth.—The common form of treated cloth is known as "varnished cambric." It may be cotton cloth impregnated and coated with either a clear varnish made of oils and fossil gums or a black varnish containing oilproof asphaltic compounds. Both are excellent dielectrics and are suitable in air or under oil. This material is used for taping leads, for insulating conductors in large transformers, and for taping the individual parts of windings in high-voltage transformers. Another use is for high-voltage air-insulated instrument transformers up to 13,800 volts.

Synthetic-resin products may be of two forms: laminated and molded. The former are usually phenolic-resin-bonded-and-impregnated sheets of paper or cloth. Perhaps we should also include here shellac-bonded fibrous materials, which are excellent in oil. The laminated products may be said to be molded, *i.e.*, a rectangular tube may be made out of a round tube or an angle out of a sheet. True molded material, however, is not laminated but is a homogeneous body of molding mixtures consisting of resin and filler. The laminated products form coil supports, tubular barriers, and other structural insulating parts. Molded resin parts are found in terminal blocks and tap changers.

Rubber will not withstand oil, so that its use is confined to leads in air-insulated units.

Wood was once more important in transformer construction than now. Early transformers were spaced and braced entirely with oil-treated pine. Some spacer blocks and braces for moderate voltages are now made of wood, usually maple.

Impregnating Materials. Varnishes.—Both air-drying and baking varnishes are used for coil impregnation, but care must be taken that the varnishes are not soluble in oil. If the normal diluent is benzene or some petroleum distillate, it is safe to suspect that the varnish will be oil soluble unless very thoroughly baked.

Shellac is oilproof and an excellent insulator, except that it softens at high temperature. An interesting use of shellac is a

shellac-oil impregnation, in which assembled transformers are impregnated in oil in which finely ground shellac is suspended. This mixture thoroughly impregnates, eliminates air pockets, and leaves a coating of hard shellac on the surface. The use of varnishes of any kind is decreasing. Improved methods of oil impregnation and shipment of transformers with oil or at least with windings in oil have proved to be even better than varnish. Dry-type units, of course, still require varnish as protection against moisture.

GUMS, once widely used, are also declining in importance. Formerly, it was considered that gum, forced as a hot liquid into a winding, would give complete filling and good heat conduction. Now, a good oil treatment is preferred. Furthermore, almost all gums are to some extent soluble in oil. Many small dry-type transformers still use gum, which gives a good solid structure that will withstand mechanical abuse and resist moisture. Repair is difficult, for the gum unites core and coils into a solid block.

TRANSFORMER OILS are the most important impregnants of transformers. Oil-treated pressboard or other fibrous material has remarkable dielectric properties, better than the equivalent oil or solid dielectric alone. Filling transformers with oil under vacuum, directly following the vacuum drying cycle, has produced much higher breakdown strengths, for the air bubbles are entirely absent. At one time, high-voltage transformers were given a "bubble test." In this procedure, a moderate voltage was applied, and the surface of the oil watched for streams of bubbles. When bubbling ceased, the voltage would be raised until bubbles appeared again. This was continued, air being eliminated by electrostatic forces, until proper test voltage was reached. With vacuum filling, this uncertain method has been discarded.

Oil as a major dielectric in transformers, or what might be termed the "ambient dielectric," will not be discussed here, since the subject is covered fully under Liquids, Chap. IV, page 77. We shall, however, describe briefly the apparatus and accessories in use on transformers for maintaining the oil in good condition. Oil has a double function: that of removing heat from core and windings and that of insulation between parts and to ground. It is effective in both creepage and puncture strengths. Deterioration of oil is detrimental to both functions. Sludging, for

example, lowers the insulating properties and also prevents free circulation for heat removal.

The aim of oil protective devices is to prevent entrance of moisture and to minimize the contact of hot oil with gas containing oxygen. The Interaire type of transformer is sealed and provided with a pure nitrogen atmosphere above the oil level. Nitrogen is fed from the usual high-pressure "bottle" through a reducing valve to maintain a positive nitrogen pressure in the tank of about ½ lb. per sq. in. When the pressure falls with lower ambient temperature, more gas is admitted. If the pressure rises, a mercury regulator permits escape of gas to the atmosphere.

The other widely used scheme is the conservator, or expansion, tank, wherein an auxiliary tank is mounted above the transformer and connected to the main tank, which is completely full of oil. The conservator tank is only partly full, there being thus room for volume changes with temperature. Air is therefore excluded from the main body of oil and is in contact with only the small surface of cold oil in the conservator. Consequently, any oxidation is slight.

Transformers with Fireproof Dielectrics.—The commonly used liquids (see Liquids, Chap. IV) are complex chlorinated compounds that are very active solvents for many organic insulating materials such as varnishes, gums, and enamels and also for finishing paints. For this reason, transformers using these ambient dielectrics instead of oil have to be designed accordingly. Untreated cloth, paper, and pressboard are satisfactory. Impregnating liquids of the usual type must be avoided.

STRUCTURAL PARTS

It has probably occurred to the reader that distribution transformer tanks seem much higher than necessary to hold the core and coils (Fig. 129). The answer in most cases is that allowance must be made for a sufficient volume of oil to remove heat effectively and permit overloads for reasonable periods. Terminal blocks are located near the top of the tank for convenience. Leads, therefore, from the windings to the terminals traverse considerable distance in many designs. The reader will note the various means of supporting these leads. In some cases, wood clamps hold the leads spaced. In others, porcelain guides are

used, and, again, laminated Bakelite tubes held in the metal frame structure. Frequently, bare leads are threaded through varnish-treated woven cotton sleeving.

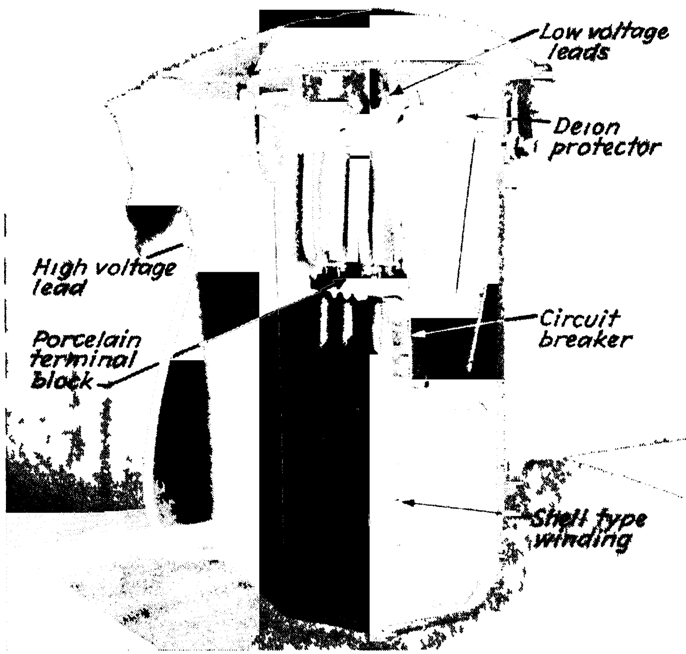


FIG 129 —Cutaway view of distribution transformer, showing relative size of transformer and tank (*Courtesy of Westinghouse Electric & Manufacturing Co*)

BUSHINGS AND TERMINALS

Transformer bushings are used to insulate the primary and secondary leads where they issue from the transformer housing or tank. There is a wide range of current and voltage requirements for the various lines of transformers manufactured. The voltage range is a few volts up to 800,000. The range in current is a few amperes up into thousands of amperes.

For the purpose of classification, the various kinds of transformer-lead outlets may be grouped as follows:

Bushings for insulated cables.

Bushings for lead-covered cables.

Bushings with the wire terminating at the end of the bushing.

Insulated-cable Bushings.—For outlets of this class, the bushing simply provides a sleeve through which the insulated wire issues. Part of the insulating value is contributed by the bushing itself, and part by the insulation on the cable. The insulation on the wires ordinarily consists of treated cloth with a protective outer braid.

For transformers that are mounted indoors, particularly for the lower voltages, the problem is simple: the outlet bushings are ordinarily made of porcelain. Sometimes the same bushing carries two wires if the voltage between them is small. An example of this is the two primary wires of current transformers, which are often carried through the same bushing.

Lead-covered-cable Bushings.—Transformers using lead-covered cables are those mounted either in manholes for subway distribution or in certain installations where the lines are carried through conduits or ducts. For transformers of 6,600 volts and below, the lead covering is carried into the transformer and terminated below the oil. For voltages above 6,600 volts, the equivalent of a pothead is ordinarily used. In this arrangement the end of the lead covering terminates in a chamber where the parts are held in alignment, and the lead covering is insulated from the conductor by means of oil or a compound that solidifies on cooling. Oil-filled potheads, sometimes used on the larger transformers, contain switches so that the transformer may be disconnected and a testing set substituted for testing the high-voltage line cables.

Terminal Bushings.—This class covers simple stud bushings, oil filled, and condenser bushings. Low-voltage stud bushings are usually constructed of solid porcelain with a hole through the center in which the terminal stud is positioned and clamped to the porcelain with gaskets and nuts or threaded through cemented hardware on the porcelain.

High-voltage bushings appear on oil circuit breakers, as well as transformers, and the construction is quite similar (Figs. 130, 131). In fact, many transformer and circuit-breaker bushings are designed to be interchangeable. The insulating parts are the same in both; the description given in Chap. X should be consulted. Though all circuit-breaker terminals are built around fixed copper studs, it is necessary for some transformers to have a hollow central tube which is only incidentally a conduc-

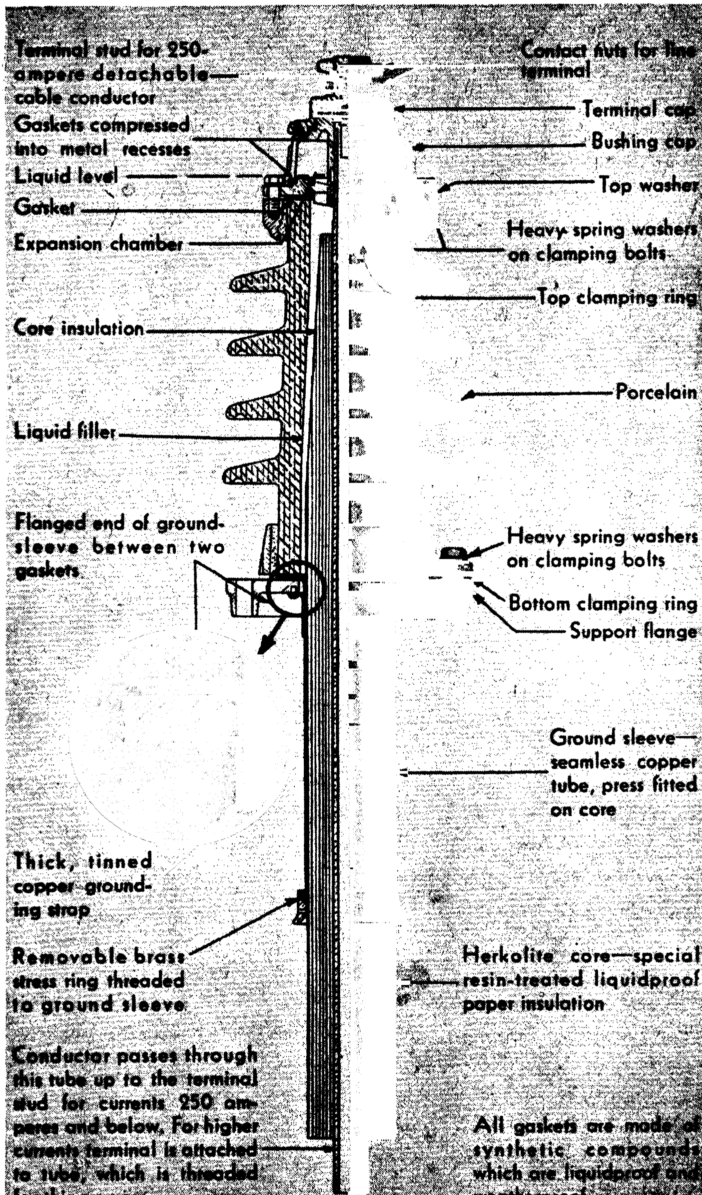


FIG. 130.—Sectional view of 34,500-volt liquid-filled transformer bushing. (*Courtesy of General Electric Co.*)

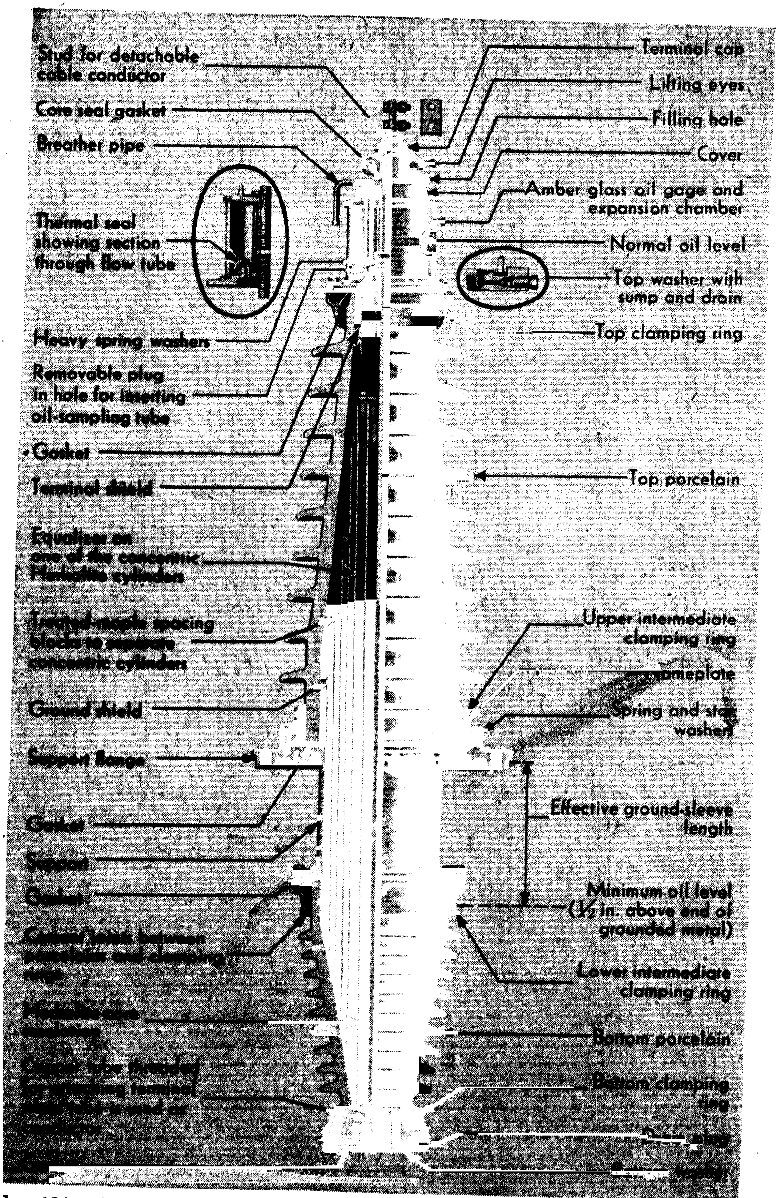


FIG. 131.—Sectional view of 115,000-volt oil-filled transformer bushing. (*Courtesy of General Electric Co.*)

tor and through which the transformer terminal wire (usually a flexible bare cable taped with insulation up to the bushing) may be "fished." The insulation can then be continuous from the coils up to the bushing. A transformer bushing usually has a lower terminal of generous curvature to reduce voltage gradient. A circuit-breaker bushing, on the other hand, has the contacts and extinction auxiliaries fastened to the lower end. Another difference is the frequent use of porcelain casings with sheds, similar to the air end, for circuit breakers. These are necessary to avoid creepage failure over the surface, which may become coated with carbon from arc decomposition of the oil. Such a requirement is absent in transformer terminals.

REACTORS

Two types of current-limiting reactors are available, dry type and oil-immersed type. The general field of application of the dry-type reactor is indoor use for all voltages up to approximately 34,500 volts and outdoor use to 25,000 volts. The oil-immersed reactor is for indoor or outdoor service at any voltage.

Dry Type.—Dry-type current-limiting reactors may be further divided into class A and class B according to the kind of insulating material used, as defined by the American Institute of Electrical Engineers Standards.

Figure 132 shows a sectional view of a typical reactor with class A insulation. The cable is insulated with cotton tape and wound into discoidal layers. Horizontal spacers provide extra layer insulation. These spacers have a rectangular hole to allow the vertical spacers to pass through. The complete winding is clamped between concrete disks by means of insulating tie rods and treated in insulating varnishes. The concrete disks have inserts cast in them to take the insulating foot studs and bolts for attaching the terminal supports. Cables are brazed into terminal supports, and all connections not bolted together are either welded or brazed.

Figure 133 shows a sectional view of a reactor with class B insulation, which will be described as a representative design. The cable of this type of reactor is insulated with an asbestos tape which has been found to have greater mechanical and dielectric strength than any commercial asbestos-braided or -felted insulations available to withstand repeated temperatures of 350°C.

The cable is wound in discoidal layers held by fire-resistant cleats. These cleats are cold-molded in hydraulic presses and will absorb less than 10 per cent of moisture by weight before

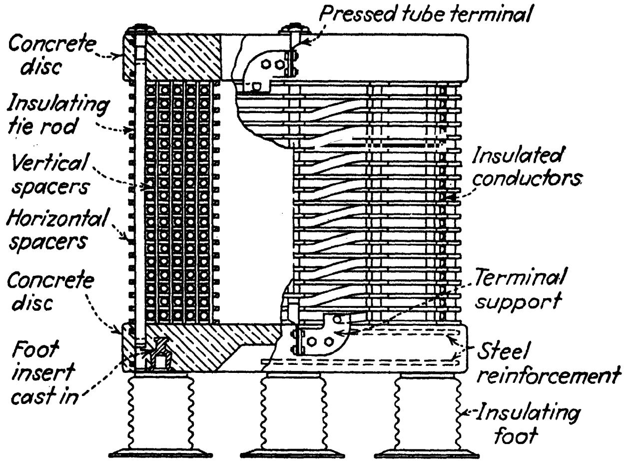


FIG. 132.—Sectional view of reactor with class A insulation. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

treatment. For outdoor coils the cleats are treated before the cable is wound into them. The cleat structure is kept in alignment by means of hickory spacers passing through holes in the

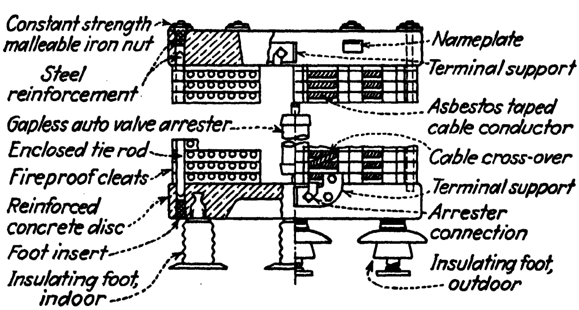


FIG. 133.—Sectional view of reactor with class B insulation. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

cleats and through the disk to be used for clamping the coil structure. A fireproof composition separates these hickory spacers from the insulated cable. Terminals and feet are attached as for class A. For outdoor coils, greater electrical clearance is used between layers of the winding as adequate

preparation for wet-weather operation; insulators for supporting the coil are standard outdoor-apparatus insulators, and tie rods and spacers are of laminated phenolic wood.

Oil-immersed Reactor.—The idea of placing reactors in a tank of oil was proposed as early as 1914 in England, but was a long time coming into common use, probably because of the obvious design problem of return-flux heating of the tank. A magnetic shield is now built either in the tank or around the reactor to take care of this problem. Mechanical fastenings for this shield must be insulated to avoid short-circuited turns. The reactor coil is wound quite like one for air insulation and slipped over an iron core which may form the supporting structure and be carried by the tank cover (Fig. 134). It is quite similar to part of a core-type transformer, except that there is only one winding. The advantages of oil-immersed reactors are that they

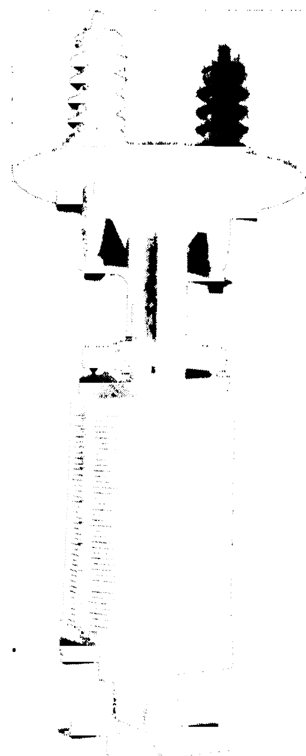


FIG. 134.—Coil, core, and terminals of iron-core, oil-immersed reactor. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Have high voltage rating.

Require small space.

Require no protective-compartment construction.

Can be placed outdoors or wherever transformers are.

Can be cooled.

Are affected by no external stray fields or force.

Have high thermal capacity.

Require no cleaning of windings.

IMPULSE STRENGTH OF TRANSFORMERS

The impulse strength of transformers has been the subject of considerable study. As a starting point, the impulse ratio for typical combinations of transformer insulation, paper, press-

board, and oil was determined by various investigators.[1] As used here, impulse ratio is defined as the full-wave ($1\frac{1}{2} \times 40$ microsec.) breakdown divided by the 1-min.-crest breakdown at 60 cycles. The figure ranges from 2.2 to 3.0, depending on the time lag of breakdown. Simply stated, this means that usual construction will stand two to three times as high a standard-impulse voltage as the crest voltage of normal frequency.

This gives a sense of confidence in the ability of a transformer to resist surges well. But, before feeling too sure, we need to know what voltages may appear in service. Of course, surges from lightning depend on directness of stroke, distance from the apparatus, and other factors. Field studies prove that high impulses several times normal voltage may be frequent. It may not, however, be so readily recognized that surges from switching on long lines may give rise to serious overvoltages. Records were taken of 854 switching surges on five important high-voltage power systems in the East.[2] Of these 854,

486 were greater than 2 × normal voltage.
185 were greater than 3 × normal voltage.
41 were greater than 4 × normal voltage.
4 were greater than 5 × normal voltage.

Hopes for the inherent strength of transformer insulation based on impulse tests vanish in the face of such data.

Generally speaking, the remedy is not to pile on more insulation. Some additional protection of end turns is frequently provided, but this is not the major protection. There are two other protective schemes available. One is to limit the value of surge that enters the transformer by means of insulation coordination. The other is to shield the windings to produce an optimum gradient for steep waves.

The problem of insulation coordination has been studied for almost 15 years; and although there is some disagreement on actual voltage values, the principle has been accepted that the flashover potentials (on surge) of transmission-line insulators and connected apparatus must be so designed as to bear a definite

[1] Montsinger, V. M., *Gen. Elec. Rev.*, vol. 40, p. 454, 1937.
Vogel, F. J., *A.I.E.E.*, vol. 52, p. 411, 1933.

[2] Montsinger, V. M., Lloyd, W. L., Clem, J. E., *A.I.E.E.*, vol. 52, p. 417, 1933.

relation to each other. Specifically, for example, we would want the line insulators to flashover first (lowest voltage). Then, if the wave reached the transformer, we would want the bushing to flashover next to protect the transformer winding, which should have the highest insulating value of the three. In this manner, relief is obtained at the least damaging points.

If all types of equipment had the same flashover characteristics, the problem would not be so difficult; but we find that they

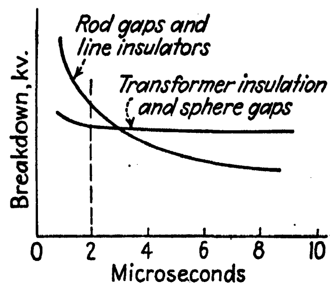


FIG. 135.—Time-lag characteristics.

differ greatly. The curve in Fig. 135 illustrates time-lag curves of two sorts. The almost horizontal curve is breakdown for transformer insulation and sphere gaps. It shows that, above 2 microsec., the surge voltage to cause breakdown in any selected time is substantially constant. Not so for rod gaps and insulators. The effect of time is marked. To cause failure in 2 microsec., the voltage must be much higher than to cause failure in 10 microsec. Designs, therefore, must be coordinated and related so that relief protection is obtained as intended.

The distribution of potential throughout the winding of a transformer with surge potential depends on the capacitance relation of parts. Under some conditions, points inside the windings may exceed, in potential, that applied to the terminal. Probably the shell-type winding produces less severe concentrations of potential than the core-type winding. However, the core type can be effectively protected with electrostatic shields, connected to the terminals and forcing a suitable gradient. For lower voltages, shields are used only at the ends; but, in high-voltage units (220 kv. and above), the shields may extend over the outside of the whole high-voltage winding (Fig. 117).

CHAPTER IX

CIRCUIT-BREAKER PRINCIPLES

Differences in construction, paralleling differences in function, serve to identify circuit-interrupting devices either as contactors or circuit breakers. Contactors (generally speaking) remain closed only when held by a magnet coil and open whenever the holding coil is deenergized. Circuit breakers are held closed by mechanical means (latches, toggles, etc.) and are opened by tripping (usually electrically) the mechanical holding devices so that gravity or spring action will open the switch. Exceptions to these generalizations can, of course, be found. Contactors are discussed in Chap. VII, page 188, Control Apparatus.

Circuit Interruption.—It is readily understood that the function of a generator is to transform mechanical energy into electrical energy. A motor accomplishes the reverse process. In these devices the function of insulation is incidental to directing the current in proper paths. A transformer is a device for transforming electrical energy from one pressure level to another, and its major insulation serves to separate the two pressure levels electrically. The transfer of energy is through the magnetic circuit. Now, when we come to a circuit breaker, we ask: What is its fundamental function? First, it is a protective device designed to operate when abnormal conditions arise. The circuit breaker disconnects or opens an electrical circuit. But through what process does this occur? We come then to the conception that such a device has as a *raison d'être*, the creation of insulation. It builds up, by one or more of several means, an insulating gap in a circuit. And this formation of an insulating barrier is accomplished, not with solid materials, but with gas or liquid (commonly air and oil). Thus the whole complex and difficult subject of arc rupture is in reality a problem in insulation, the transition from a conducting path to a nonconducting gap. We may therefore properly consider the elements of circuit interruption before discussing the means by which practical circuit breakers accomplish the desired end.

When we analyze the circuit-interrupting phenomenon, we marvel at the feat accomplished and wonder how old designs of circuit breakers ever functioned so successfully. The device must perform a remarkable transformation in a few millionths of a second. When it is closed and during the arcing period, the switch may carry thousands of amperes with very little voltage drop. An instant later we require that it be an insulator with reversed conditions—carrying negligible current and capable of withstanding a circuit potential that may be thousands of volts. In interrupting an alternating-current arc, this quick shift may occur in a few microseconds after a current-wave zero. If the problem were a new one with no background of experience, the first reaction of a materials engineer would be that no material could be found to do the job. The specifications are too rigid. But we know that air and oil both serve very well. We have not yet found anything else that will even approach the performance of gases or the gaseous products of oil decomposition.

Direct-current Arcs.—The opening of direct-current circuits which are usually at low voltage is quite different from the problem in alternating-current circuits. In the direct-current case an arc must be drawn out or magnetically forced out to a length sufficient to break the arc. The break occurs when the voltage necessary to maintain the arc exceeds the circuit voltage. The length may vary with current to be interrupted and with other conditions that must be considered in design, but the problem is relatively simple.

Alternating-current Arcs.—Opening an alternating-current circuit is by no means so simple. Here time is a vital factor. The current is varying periodically, passing through zero twice per cycle. The voltage which is tending to maintain the arc current is also varying cyclically and possibly out of time phase with the current. For example, in a purely inductive circuit the current zero coincides with a voltage peak in time. If the circuit is to be interrupted, then, the arc path must change from conduction to insulation in zero time. This would be impossible, but of course a pure inductance would also never be found in a practical circuit. However, the transition must take place in a few microseconds to a few hundred microseconds, at best a very short time for a complete reversal of properties. Whether the time available is long or short depends not on the normal voltage, frequency, etc., of

the circuit, but on the transient characteristics—the natural frequency of oscillation. The arc during interruption is responsible for the successful transfer from conductor to insulator; and, as Dr. Slepian remarks,[1] the arc is not an inconvenient accompaniment of switching, to be reduced to a minimum, but an essential factor that is a necessity for circuit interruption.

A veritable race goes on in an alternating-current arc, the outcome determining whether the circuit opens as we wish or the arc reignites to start the race over again. The contest is between the recovery of dielectric strength in the arc path and the recovery of circuit voltage. The first is dependent on the progress of deionization, and the second depends on circuit conditions, as noted above. Since circuit breakers must be made to operate under unfavorable circuit conditions (for example, near a large generating station), means must be devised for increasing the rate of deionization of the arc path.

Ionization and deionization are going on simultaneously in an arc stream. Ionization by collision contributes somewhat, and probably thermal ionization in the heated arc is a source of ions. We know also that ionization is in some degree proportional to the electric gradient, so that at high voltages, the problem is made more difficult. Offsetting the process of ionization, deionization is proceeding through recombination of ions, and by ions entering the electrode surface.

Keeping in mind this ion race, which may be likened to the fight in the human body between white corpuscles and germs of infection, we may first determine what fundamental facts have been observed, next decide what principles are essential in reaching the goal of successful interruption, and last discuss practical means of designing devices in accordance with the principles. There are several successful circuit-breaker designs in use, operating on apparently widely different plans of action; but most of them accomplish the desired results by different approaches to a few fundamentals.

We must make a distinction, according to Dr. Slepian,[2] between short arcs and long arcs. The short alternating-current arc may be defined as one in which the cathode phenomena predominate. The major recovery of dielectric strength takes place in a layer next to the cathode, and this occurs almost instantly. The curve

[1] "Theory of Deion Circuit Breakers," *A.I.E.E.*, vol. 48, p. 523, 1929.
[2] "Extinction of an A-c Arc," *A.I.E.E.*, vol. 47, p. 1398, 1927–1928.

in Fig. 136 illustrates this. A strength of 250 volts is recovered in a thin air layer immediately, and subsequently increments of 1 million volts per sec. or more may follow. Dr. Slepian's theoretical analysis demonstrates that, for a 2,300-volt circuit, a short arc would require at least 150 microsec. to recover sufficient dielectric strength. Faster deionization is possible with the aid of special means, as shown later.

A long alternating-current arc is a more complex phenomena and may be described as one in which most of the dielectric strength is furnished by the portion of arc not adjacent to the cathode. By inference, then, the short arc is successfully treated only as a low-voltage problem, and the long arc covers the usual high-voltage circuit-breaker condition. Short-arc interruption is accomplished in the main by providing adequate contact between gas and the cathode surfaces so that deionization is rapid.

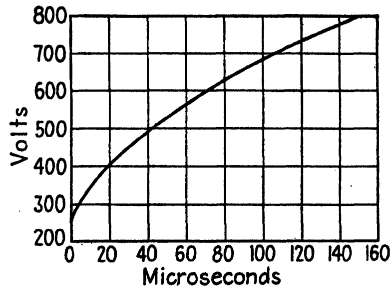


FIG. 136.—Recovery of dielectric strength of air in a short arc. (*Slepian.*)

Long-arc extinction, on the other hand, results from introducing deionizing means into the arc stream in the form of un-ionized gas, either as gas directly or as gas from decomposition of fresh oil. A variation of the short-arc idea that extends its usefulness to voltages as high as 15,000 in air is the formation of several short arcs in series, by interposing metal plates, screens, or grids which act as intermediate cathodes. The Deion air circuit breaker has been developed on this plan. An additional feature is the movement of the arc over the metal surfaces by magnetic fields, at velocities of 500 to 1,500 ft. per sec. This prevents burning, even with currents of several thousand amperes. Motion of the arc continues until deionization is accomplished. This apparently demonstrates that arcs with relatively cold cathodes can exist.

Oil Circuit Breakers.—Oil is used, especially for long-arc extinction, in higher voltage breakers, because it is a more effective means of deionization than air. But the means of functioning is not greatly different. An oil circuit breaker is also a gas device. The arc decomposes oil locally and forms hydrocarbon gases which are un-ionized and serve to absorb the arc

ionization. At one time, the formation of a gas bubble in oil circuit breakers was regarded as evidence of ineffectual design principles, but now we know the gas is necessary. What we must do, however, is form the gas quickly, move it into the arc forcibly, and limit the total volume of gas evolved during interruption. The arc must be kept close to bodies of fresh un-ionized oil which will create the deionizing gas required. This intimate contact may be obtained in many ways, for example, by cross blasts of oil developed by arcs in restricted oil pockets, by mechanical force of pistons and compressed gas, by magnetic blowouts for directing the arc into slots or holes, etc.

A further requirement for effective arc rupture is that the gas shall have turbulence to distribute the un-ionized volumes throughout the arc length. It has been found that the arc should be moved at once away from the main contacts into a position where it may be controlled and "worked on." Then a higher voltage gradient can be developed at the main contacts than if the whole deionizing function is attempted at the main contacts. Once under directional control, the arc can be divided into multiple breaks in series, driven into a slot made of material that gives off deionizing gas (fiber, for example), forced into an oil-filled narrow space, or driven out into large volumes of fresh oil. The division into series arcs, mentioned under Alternating Current Arcs above and illustrated by the air Deion breaker, is also practiced in oil circuit breakers. Some of the most successful devices offered for high voltages by several manufacturers contain up to 10 breaks in series.

The division of arcs brings into consideration the question of voltage gradient. If the distribution is nonuniform, the addition of breaks may be quite ineffective. When we speak of gradient, we immediately find that it is not a stable condition with respect to time. During arc conduction, the gradient is determined by conductivities of the sections of the complete path. When the circuit is open, the distribution of potential corresponds to capacitance relations to parts and to ground, which may produce an unfavorable division of voltage. Electrostatic balancing must therefore be applied to most structures using series breaks. This is accomplished by means discussed in Chap. X, Circuit-breaker Constructions. A static shield is also applied in the high-voltage Deion air circuit breaker.

CHAPTER X

CIRCUIT-BREAKER CONSTRUCTIONS

Up to the present point, we have been concerned with the circuit breaker as a device for making, almost magically, insulation out of a conductor. We have considered the arc itself as a means of insulating. We have to keep in mind, also, that the active elements of a circuit breaker must be insulated from the supports and ground, and that insulation appears in the construction, functioning both electrically and mechanically. We shall point out both the insulating members and the method of arc interruption.

Circuit breakers are usually divided into two major groups: air circuit breakers (contacts open in air) and oil circuit breakers (contacts open under insulating oil).

AIR CIRCUIT BREAKERS

Carbon Breakers.—Figure 137 discloses the simplicity of the insulating problem in air circuit breakers. The principal insulation is the panel upon which the main contacts are mounted. Common materials used are slate, ebony asbestos, and marble. Wherever shock or vibration is to be expected, ebony asbestos is preferred.

Another point not so obvious is the insulation of the operating parts from the main circuit parts. Usually, the main brush contact is mounted directly on the mechanical parts, so that the frame and linkage are "alive." In this construction the operating handle, the tripping bar, and the plunger are all insulated from the mechanism. Included with the plunger is the adjustment for varying the tripping current, a part handled by the operator and therefore insulated. Molded parts (Bakelite) are usually found in the locations mentioned. Where the whole frame and mechanism are "dead," the moving contact parts (main brush and arcing tip) must be insulated. In some designs, sheets of mica plate are inserted, and insulated bolts pass from the support through holes in the contact into a block on the

opposite side. Another scheme is to mount the contacts on molded or laminated Bakelite blocks with insulated bolts.

Trip coils may be provided to operate in various ways: from excessive current (series), from a distant point whenever desired

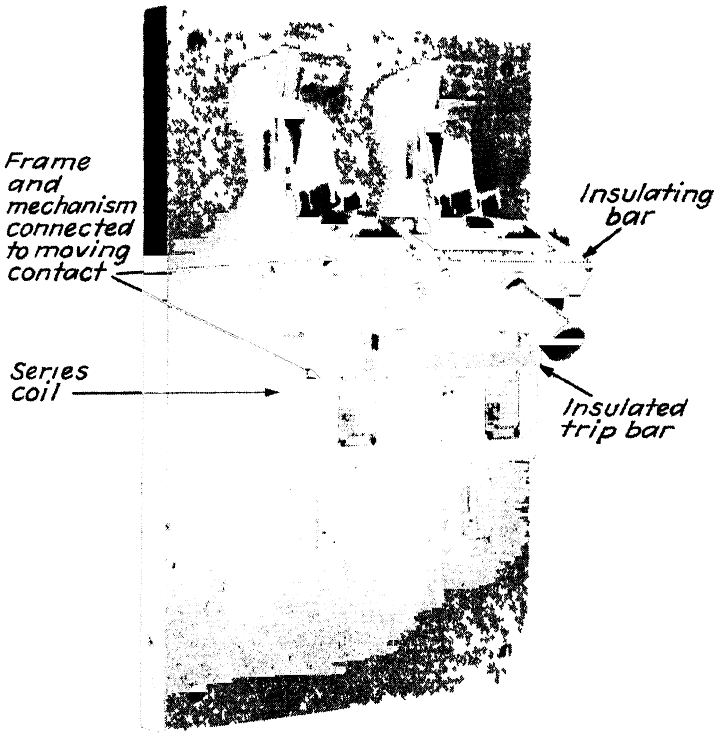


FIG. 137.—Two-pole air circuit breaker (carbon breaker) (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

(shunt), automatically when voltage fails (holding coil), or on reversal of power. The series coil, consisting of a few turns of edge-wound bare copper bar or strap, is fastened to the main stud. The trip plunger operates inside the series coil (as a solenoid) and is made with an insulating tip or may be metal with an insulating tube over it. Shunt coils, holding coils, and closing solenoids are of the usual construction found in control devices, described elsewhere. Closing coils often operate levers that have an insulating link in one of the members.

Grouping of air circuit breakers for simultaneous operation requires that the separate units be insulated from each other but mechanically tied together, both for closing and tripping. This is usually accomplished by bars of phenolic laminated material securely bolted to the mechanisms and to the closing handle on the bar.

High-voltage and High-speed Air Circuit Breakers.—Special forms have been developed for heavy duty, particularly for rail-

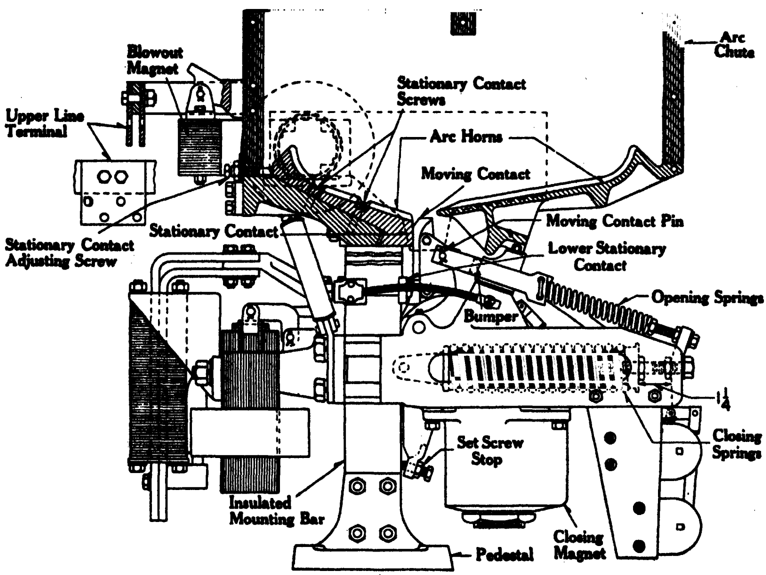


FIG. 138.—High-speed air circuit breaker for high-voltage railway service. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

way service, sometimes at high voltages (Fig. 138). Here the mechanical parts take on formidable proportions to withstand the extreme acceleration of parts and the mechanical reactions of the current being interrupted. The controlling mechanism (closing and tripping) may be apart from the main device and connection obtained through an operating rod. This may be tough wood (hickory), laminated wood, resin bonded; or rolled phenolic tubing.

Another insulating part appears in these breakers—the arc chute. In simple form, this is an enclosed channel in which the arc is dissipated and kept from striking to surrounding objects.

Further division of the channel into parallel spaces or, in the other direction, to form arc splitters for lengthening the arc path, is practiced in designs for high voltage and current. For all these parts an insulating barrier material is needed that will withstand the high arc temperature and will not become coated with deposits of condensed metal vapor. One would expect that a heat-resisting ceramic material would be best, but only in limited applications is such a material strong enough in sections thin enough to be used. The practical solution, which is, however, not perfect, is asbestos molded in plates with an inorganic bond.

A modification of the conventional air circuit breaker is found in the Deion air breaker, which has deionizing chambers containing grids into which the arc is directed. These grids act to cool and snuff out the arc in a manner similar to their operation in contactors and oil circuit breakers. The interrupting capacity and life of a given size of breaker parts can in this way be increased. These grids are constructed of fiber plates with magnetic inserts to direct the arc into the grids.

Deion Air Circuit Breaker for High Voltages.—The possibility of extending the short-arc extinction, particularly in air, to higher voltages by division into series arcs in contact with deionizing cathodes has been mentioned. An interesting development of this idea is a form of Deion air breaker for 15,000 volts, intended for service where an oil circuit breaker would involve too great a fire hazard. Each short arc can be conservatively rated at 110 volts r.m.s., so that 136 series arcs would be required for 15,000 volts.

The series of functions of this breaker follow in this order: An arc is drawn between two main stationary contacts (insulated from the supports) and is quickly transferred to arcing contacts which are connected so that a "blow-in" coil, carrying the heavy current, produces a magnetic field which again transfers the arc to a deionizing chamber (Fig. 139). This process of moving the arc away from the main contacts into a position where it can be manipulated is also present in many designs of oil circuit breakers. There is the suggestion of the luring of an animal into a trap from which there is no escape.

What goes on in the "trap" can now be explained. There are two circuits in the deionizing chamber. First is a central tubular conductor energized as part of a one-turn loop and blow-in coil

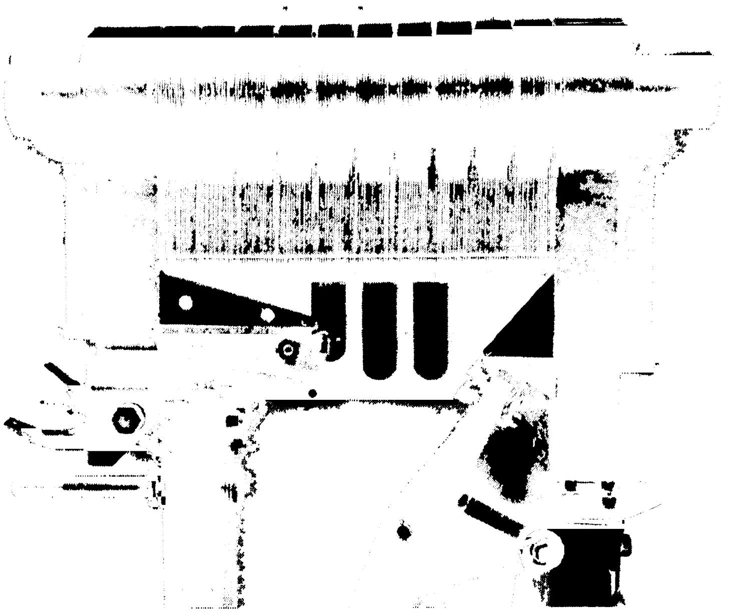


FIG. 139.—Deionizing stack of 15,000-volt circuit breaker, with static shield removed. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

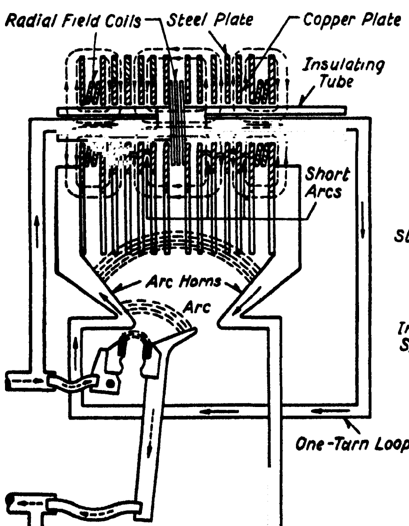


FIG. 140.—15,000-volt air Deion circuit-breaker circuits. (*Courtesy of Westing-house Electric & Manufacturing Co.*)

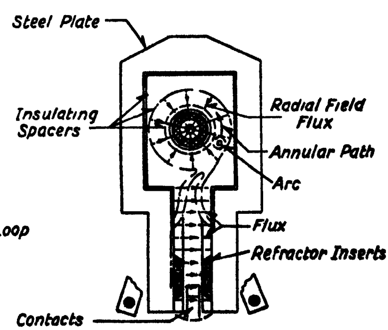


FIG. 141.—Mechanism for spinning the arc. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

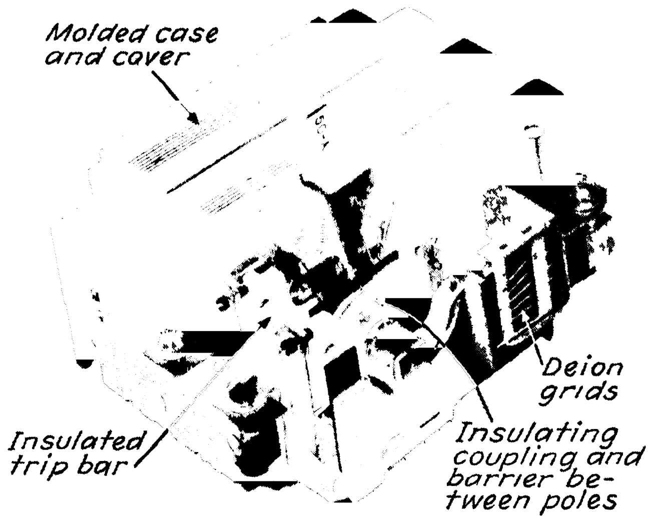


FIG 142 —250-volt 10- to 25-amp Deion circuit breaker (*Courtesy of Westinghouse Electric & Manufacturing Co*)

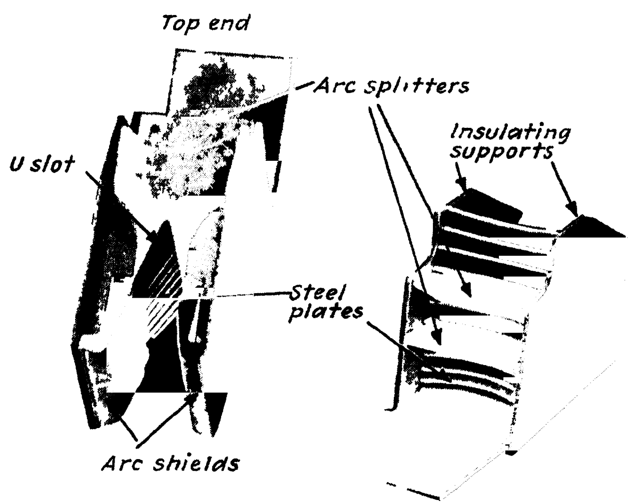


FIG 143 —Deion structure of 600-volt, 225-amp circuit breaker (*Courtesy of Westinghouse Electric & Manufacturing Co*)

(Fig. 140). At intervals, surrounding this tube are perpendicular magnetic plates to supply additional field to pull the arc into the structure. The central conductor is covered with an insulating tube. Thus far, the mechanism is only for enticing the arc from the arcing contacts.

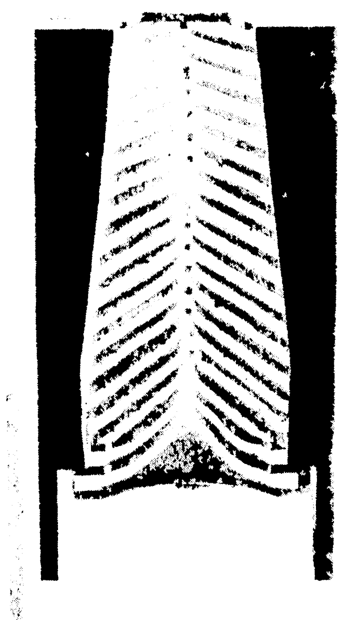


FIG. 144.—Bottom view of Deion arc chute showing V-slots in insulating plates. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The deionizing circuit is made up of copper plates with circular top portion and an entering throat at the bottom. Many of these plates are stacked together over the central tube, spaced with insulation. Magnetic plates are inserted at intervals in the copper pile and insulated therefrom.

Inserted in this stack at several points are the radial field coils. These coils are connected in shunt to the copper plates and thus carry current proportional to the drop across the gaps. Their

purpose is to start the arc spinning in a circular path around the copper plates until the series short arcs are all deionized in their respective cells (Fig. 141). The rate of arc travel has been stated as 220,000 ft. per min. The long arc, therefore, on being drawn into the groove formed by the succession of copper-plate throats, is cut into many series arcs which start to travel in circles between the plates and are extinguished as cold-cathode arcs.

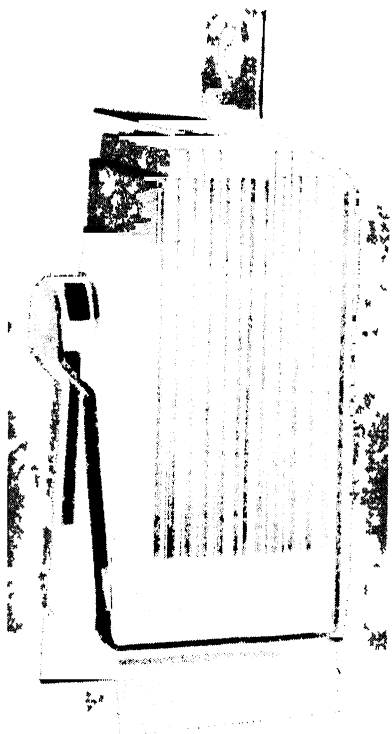


FIG 145—Deion grid with arc spinner for 600-volt circuit breaker. *(Courtesy of Westinghouse Electric & Manufacturing Co)*

The whole stack is covered with an insulating shield into which are built electrostatic distributing plates to produce uniform gradients across the gaps. On the outside of the shield are additional parts of the blow-in magnet system.

Low-voltage Air Circuit Breakers with Arc-extinction Devices.—It is a remarkable and fortunate phenomenon that thin layers of gas adjacent to cathodes recover a useful dielectric strength almost immediately at the first current zero. We may count on approximately 250 volts crest or 175 volts r.m.s. recovery, so that 115-volt alternating-current circuits offer very little difficulty. Even 230-volt circuits are not serious. The division of higher voltage arcs into series arcs within the range extinguishable as "short arcs" has been discussed, and the question is natural as to how far down in voltage it is useful to employ the subdivision principle.

There are applications for small circuit breakers, where small size, good appearance, and safety for inexperienced persons are

sought. These include panel boards, distribution switchboards, and load centers, either for lighting or small power circuits (Fig. 142). The capacities cover the range of 125 to 600 volts alternating current and 15 to 600 amp. For this service, several manufacturers offer switches utilizing the deionizing grids in simple form. In designs for the lower current ratings, the arc is

Fig. 146.—Deion spinner showing spiral path made by arc during extinguishing action. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

drawn in the throat or slot of a series of spaced metal plates in the arc chamber (Figs. 143, 144). Cooling and deionizing of the arc quickly open the circuit without the usual "fireworks" and noise associated with conventional open-construction air breakers, usually classed as "carbon" breakers. The whole mechanism is built into an inconceivably small space inside an insulating box (molded Bakelite). Even in opening short circuits of several thousand amperes, practically no flame appears at the vents. In higher capacities (225 amp. and up), the familiar "arc-spinning" idea is incorporated (Figs. 145, 146). By proper

configuration of the current circuit at the arc chamber, a magnetic effect is obtained which causes the arc to enter the grids and be broken up and the separate sections to rotate until "exhausted."

A reason for paying so much attention to the effective rupture of arcs in these low-voltage panel-board breakers is the emergency requirement for interrupting great overloads. Circuit constants and the connected supply capacity are often such that large short-circuit values are possible. A glance at the following underwriters' requirements shows the expected performance.

1. The breaker must operate satisfactorily 6,000 times at 100 per cent load.
2. The breaker must operate satisfactorily 50 times on 600 per cent rating at 50 per cent power factor and rated voltage.
3. Breakers rated up to 50 amp. must open three successive short circuits of 5,000 amp. at 50 per cent power factor; above 50 amp. rating, the test is 10,000 amp.
4. After the short-circuit test, the tripping time on 200 per cent load must be normal.

The use of quenching devices thus becomes necessary for rupturing duty and also to obtain the desired life of contacts.

OIL CIRCUIT BREAKERS

Arc-extinction Devices.—Concentrations of high-voltage power systems have demanded protecting circuit breakers of capacities undreamed of before systematic study of short circuits revealed the need. For example, an interrupting capacity of 2½ million kva. is not at all uncommon. To open such a circuit by "brute force," *i.e.*, by drawing out an arc under oil from simple contacts, would require tanks and mechanisms of a size wholly out of reason. We have witnessed over a period of years the development of several devices for snuffing out arcs in very short times (½ to 2 cycles). Of these various methods, three interesting types will be described, *viz.:* the Deion grid, the oil blast, and the gas blast.

Deion Grid.—The interrupting element, or stack of grid plates from which the device has derived its name, is shown in Fig. 147, one of these grid assemblies being supported from each stationary-contact element. The particular grid shown here is designed for 161-kv. service and is made up of 13 similar units

such as are shown in Fig. 148, each unit in turn being made up of plate elements of insulating and magnetic material as shown in Fig. 149. Each grid plate carries a slotted opening, the purpose of which will be explained later, and four holes so arranged that, when the several units are stacked up in the completed grid,

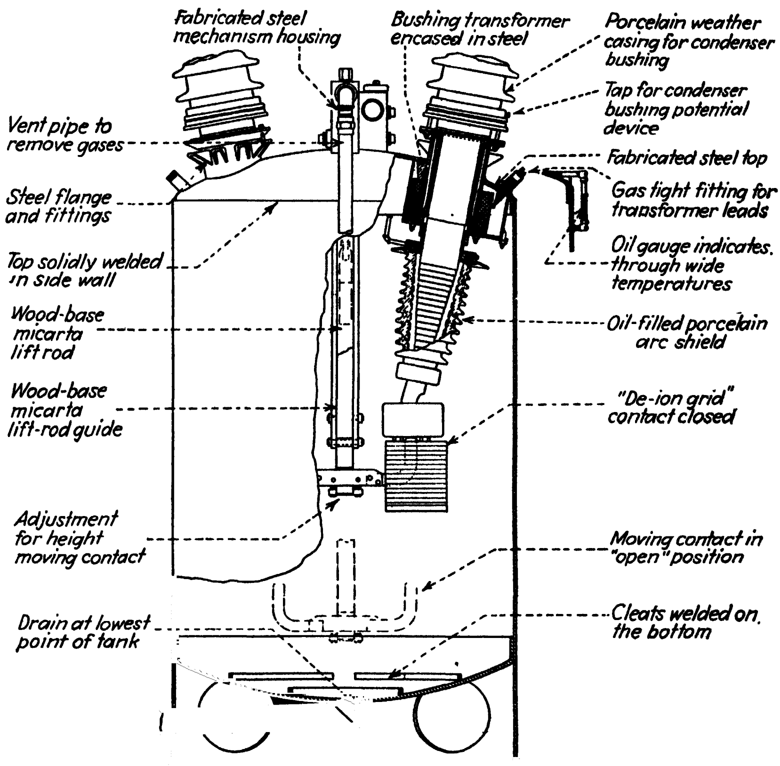


FIG. 147.—Sectional view of 161-kv. oil circuit breaker with Deion grids on terminals. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

insulated studs can be passed through for the purpose of clamping the units firmly together and for supporting the grid from the stationary-contact element. The bottom plate, or lowermost unit of the stack as shown in Fig. 150, is a single plate of insulating material serving as an anchorage for the clamping studs as well as a guide to ensure accurate entry of the movable-contact element into the grid during the closing contact movement.

As shown in Figs. 148 and 149, the slotted openings in each plate element all register in the completed grid to form a single deep and relatively narrow groove, extending throughout its length. This groove is closed at one end of the grid but open for its entire length at the other end, the two grids in any pole unit

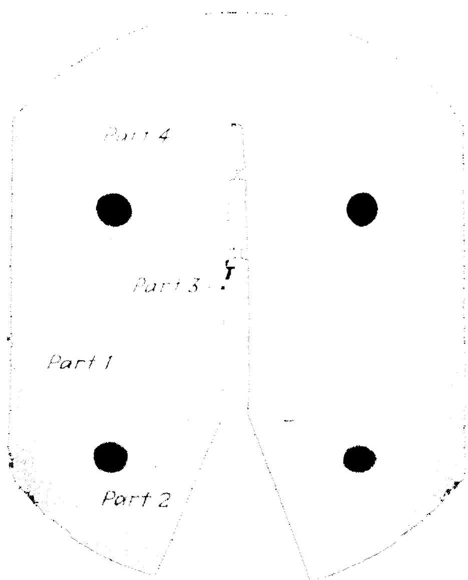


FIG. 148.—Deion grid unit for oil circuit breaker. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

being arranged so that the long axes of these grooves lie in the plane of the movable-contact element with the open end of the two grooves facing each other. The ends of the movable-contact element extend through the open ends of the grooves well into the narrow portion, one end of the contact in each grid. As the contacts part on opening, the movable element passes downward through the groove and on to the end of the stroke, well beyond the grids, leaving an ample space of clean oil between the contact surfaces and the bottom of the grid to ensure adequate insulation in the open position of the breaker. The arc produced by parting of the contacts is drawn and extinguished in this narrow groove, closed on all sides except for the opening at the inner end,

necessary to permit contact movement, and the openings at the top and bottom of the grid.

A grid unit is assembled with part 3 on the bottom (circular holes form oil pockets), then part 1, and then parts 2 and 4, fitting together in the same plane. The oil in the pockets of part 3 furnishes additional cooling means to the arc stream.

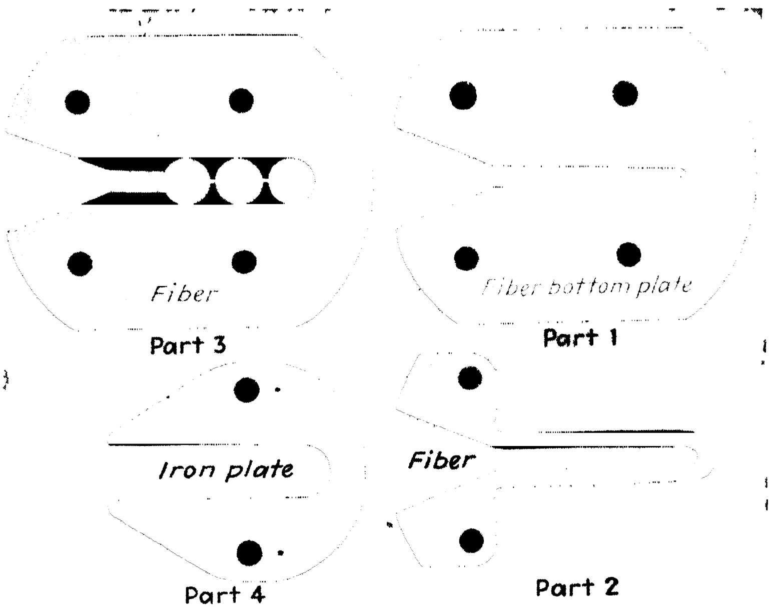


FIG. 149.—Deion grid elements for oil circuit breaker. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The iron-plate elements in the grid are inserted to produce a magnetic field for the purpose of moving the arc toward the closed end of the groove after it is drawn. As shown in Figs. 148 and 149 each iron plate is roughly horseshoe-shaped, forming a partial magnetic circuit with an air gap corresponding to the slotted opening in the insulating-plate elements. As the contacts part when the breaker opens, an arc is drawn between the stationary and moving elements in the narrow groove of the grid. As the contact moves downward toward the open position, the arc is drawn through the air gap of the iron plate, giving rise to a magnetomotive force in the iron circuit and across the air gap. As the contact moves downward, the same effect is produced

in the succeeding iron plate, and so on until the arc is extinguished. These magnetomotive forces are applied almost entirely across the air gaps in the several grid plates, distorting and strengthening the magnetic field around the arc in such manner that the arc is moved toward the closed end of the magnetic circuit, which is also the closed end of the groove.

FIG. 150.—Deion-grid oil circuit breaker for 15,000 volts. Three poles in one tank. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

From the description here given, it will be apparent that the construction of these grids admits of a large number of variations or modifications that may prove desirable or necessary to meet any particular circuit condition. The number of unit groups in the grid may easily be decreased or increased to meet service-voltage requirements; the number of iron plates and the amount of iron in each plate may be varied without difficulty; the size

of the slots, the size of the plates themselves, or even their material may all be changed at will.

It will be evident that an arc moving toward the closed end of the groove is, in effect, being forced against a solid wall of oil throughout its entire length, resulting in a high rate of decomposition of oil with an accompanying continuous and adequate supply of fresh un-ionized gas. This gas cannot escape except through the arc stream, since the arc fills the open end of the groove. Owing to the driving power behind the arc, the gas is forced to pass through the arc stream, diluting it with small volumes of un-ionized gas, while current is flowing, which act as deionizing surfaces after the current zero is reached. An additional deionizing effect is obtained from the sides of the groove where the arc impinges as it moves. The insulating-plate elements in the grid are of absorbent material, containing in their submerged condition considerable oil. As the arc passes over the edges of these grid plates exposed in the sides of the groove, the heat forces this material to give off its oil, which is also volatilized and thrown turbulently into the arc stream. This characteristic of giving off oil and creating a gas film along the edges of the plate elements also serves to protect these from burning under the heat of the arc. Large numbers of interrupting tests have been made with a single set of grids without appreciable burning.

OIL-BLAST CIRCUIT BREAKER.—Slepian[1] and Schwager[2] claim that all oil circuit breakers function because of a gas-blast principle, the gas being formed by oil decomposition in one or more ways. Others, notably Prince,[3] believe that the properties of oil itself as a liquid have a major part in arc extinction. Oil-blast circuit breakers of various forms have been in use and have performed with marked success, even though the exact theory of operation may be disputed.

One of the earlier types of oil blast is the explosion-pot live-tank breaker (Fig. 151). The general design has inverted explosion pots with the main contacts in air, as indicated. The explosion pot consists of a steel cylindrical oil tank with insulated

[1] "Extinction of A-c Arc," *A.I.E.E.*, vol. 47, p. 1398, 1927–1928.

[2] "Expulsion Breaker," *A.I.E.E.*, vol. 53, p. 1108, 1934.

[3] PRINCE, D. C., and W. F. SKEATS, "Oil Blast Circuit Breaker," A.I.E.E., vol. 50, p. 506, 2931.

lining supported on a porcelain post set in a base with clamp fittings and mounting bolts. Inside the oil tank is a system of baffle plates, held in place and supported from the oil-tank top.

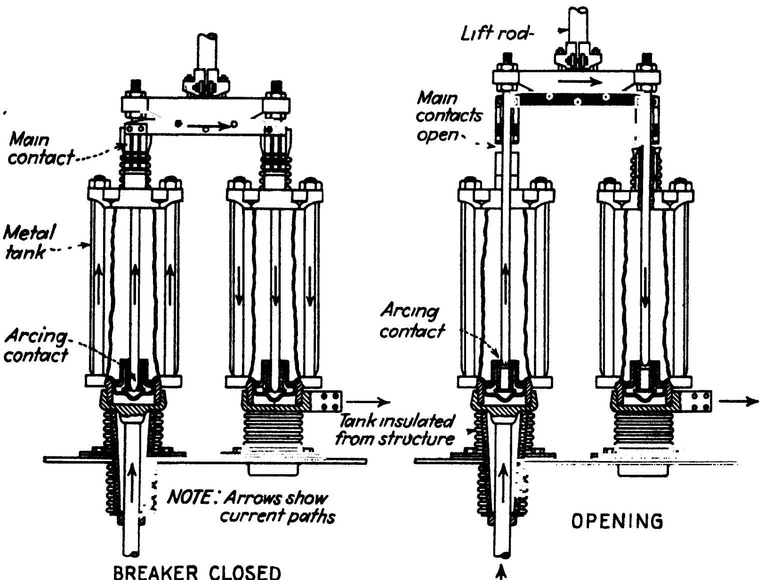


FIG. 151.—Live-tank oil-blast circuit breaker. (*Courtesy of General Electric Co.*)

The lowest plate is reinforced with steel and makes a tight fit with the oil-tank lining by means of a leather packing. A movable plunger rod attached to a crossarm projects into the

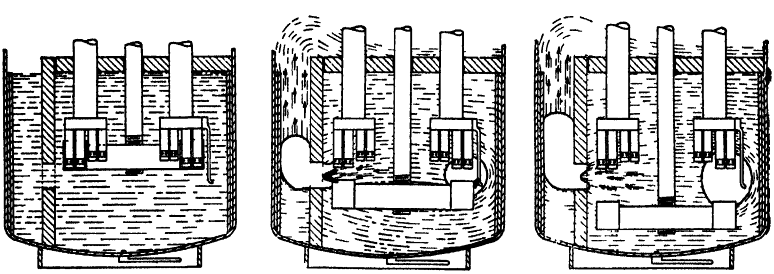


FIG. 152.—Action of oil-blast circuit breaker. Left, closed; center, interrupting; right, interruption complete. (*Courtesy of General Electric Co.*)

explosion-pot throat and engages with a segmental circular wedge which is the stationary member of the arcing contacts. When the breaker is tripped, the movable plunger rod moves up out

of the segmental wedge, drawing an arc. The arc gasifies the oil, rapidly creating a very high pressure in the cylinder which forces the moving plunger out of the cylinder, extinguishing the arc. Two explosion pots are provided for each pole unit; *i.e.*, there are two breaks in series per phase.

Separation chambers, above the explosion pots, contain a quantity

Fig. 153.—Blast chamber of oil-blast circuit breaker. (*Courtesy of General Electric Co.*)

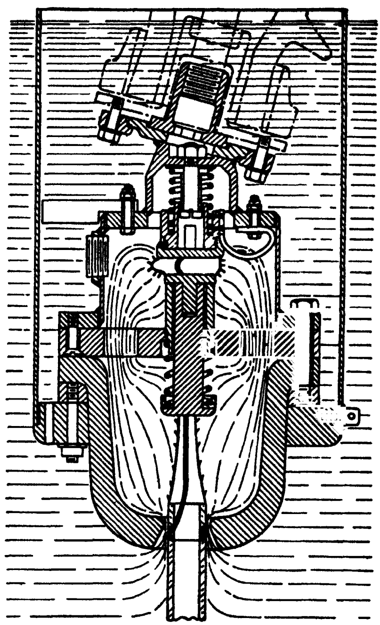


Fig. 154.—Radial blast with insulating chamber, oil-blast circuit breaker. (*Courtesy of General Electric Co.*)

of quartz pebbles through which the gas has to pass to escape. The oil condensed drains through the perforated disk and exhaust opening in the breaker top back into the explosion chamber.

The oil-blast principle (Fig. 152) has been applied in many forms to suit various conditions of voltage, current, and interrupting duty. These modifications are described through specific names, such as oil-blast chamber, radial oil blast, series blast, cross blast, and impulse breaker.

In the *blast-chamber*, sometimes known as "explosion-pot," type, the tank is partitioned with an insulating barrier in which holes are made (Fig. 153). The arc is drawn in the enclosed space, forming gas which builds up pressure on the oil and forces the arc and gas out of the ventholes in the barrier. The tank lining and enclosure are made of laminated Bakelite board.

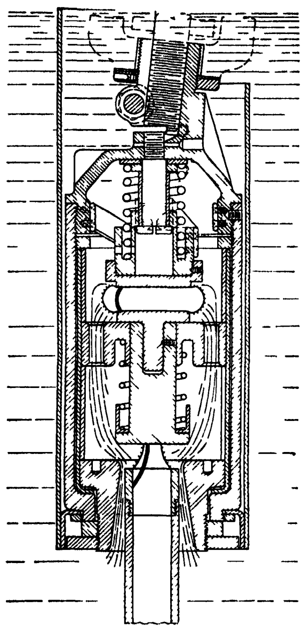


FIG. 155.—Radial blast with metal chamber, oil-blast circuit breaker. (*Courtesy of General Electric Co.*)

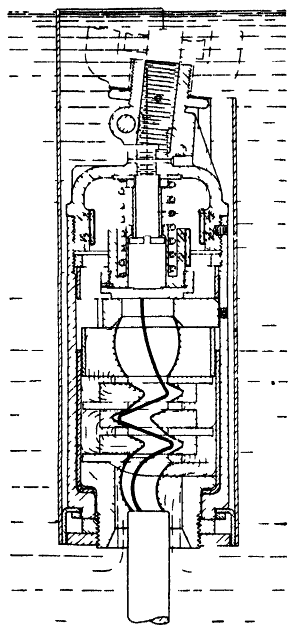


FIG. 156.—Series-blast oil circuit breaker. (*Courtesy of General Electric Co.*)

The *radial blast*, used for high-voltage breakers, has explosion chambers (metal for 69 kv. and below and molded insulation above 69 kv.) attached to the bushings (Figs. 154, 155). For the higher voltage ratings, the blast structure is mounted inside a chamber of molded insulation, with a bottom hole closely fitting the hollow cylindrical moving contact. When the hole is closed, the current is carried through the moving contact, a floating contact, and the stationary contact. This arc decomposes oil, and the resulting gas creates a pressure of approximately 150 to 200 lb. per sq. in. on the oil in the chamber. Under this pressure,

oil moves into the hollow moving contact and also toward the throat of the chamber, sweeping gas with it. In the meantime, the floating contact reaches a stop, and then there are two arcs in series, both generating gas.

At a current zero, the oil breaks through the arc stream and forms a wall of liquid which has the effect of pinching off the arc at about the time the moving contact emerges from the chamber. The extinguishing effect either may be ascribed to the high dielectric strength of liquid oil or may be in accordance with Slepian's conception of gas deionization by the forced intimate contact of fresh gas from the oil and the arc stream. The total arc length required by this scheme is very short compared with a "plain break" device. The oil velocity at the break may reach 150 ft. per sec., kinetic energy having resulted from the potential energy of the pressure developed in the explosion chamber.

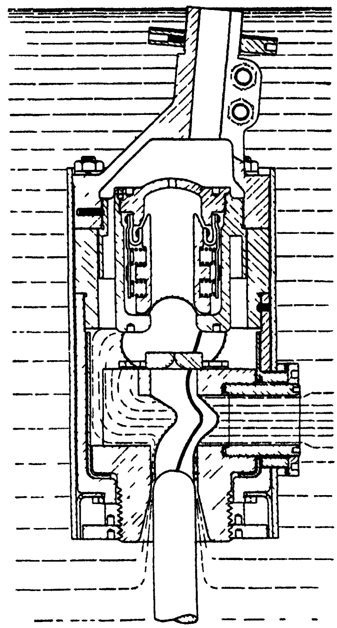


FIG. 157.—Cross-blast oil circuit breaker. (*Courtesy of General Electric Co.*)

The *series-blast* breaker is made in moderate ratings up to 69 kv. and develops the blast scheme by drawing a single arc through an insulating chamber having recesses spaced alternately so that a blast of oil is forced into the arc from opposite directions as the moving contact is withdrawn (Fig. 156). This reminds one of a boxer delivering a right, a left, a right; and the arc is out for the count.

Heavy-duty breakers in the 15-kv. range employ a *cross blast* in which there are again three contacts in series and two arcs drawn. The first generates the pressure required for forcing a blast of oil perpendicular to the main arc path (Fig. 157).

The *impulse* oil-blast circuit breaker developed for Boulder Dam is interesting from several angles. First of all, it shows the oil-blast construction applied to high voltage (287 kv.)

(Fig. 158). It is, next, of importance in demonstrating the effectiveness of subdividing the arc. When Slepian's "short-arc" conditions are obtained, whether by Deion grid cathodes or by separate gaps provided with oil blast, the adding of gaps increases rupturing capacity practically in a linear relation,

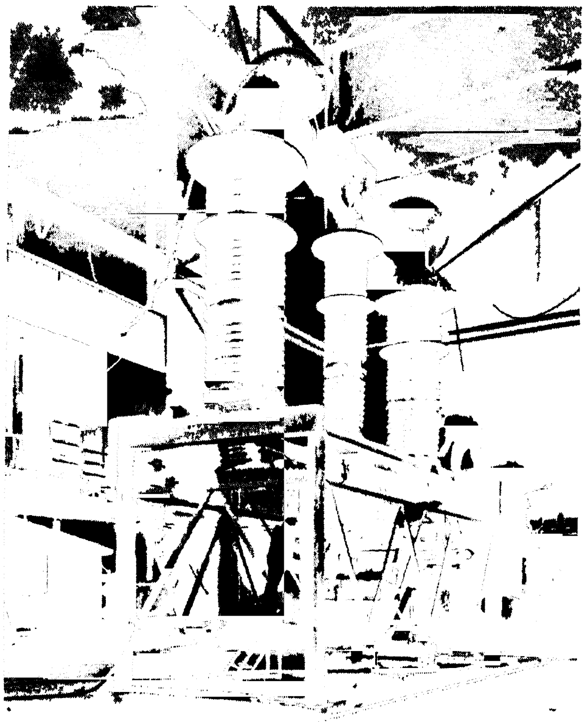


FIG. 158—Impulse oil circuit breaker, 287,000 volts, for use on Boulder Dam transmission line City of Los Angeles, Department of Water and Power (*Courtesy of General Electric Co.*)

provided that suitable potential grading is furnished. The third reason for the interest in this design is that it marks a departure from usual practice in tank and other structural details. It belongs to the class already used in Europe and given the name "oil-poor" breakers. The name arises from the fact that a small volume of oil is used, compared with conventional designs.

Each breaker pole consists of two horizontal molded insulation tubes (Fig. 159) mounted on porcelain columns. Each tube is

divided inside by a horizontal insulating board about on the diameter, sealing off the lower half from the upper except for two small ports above each of four contacts. The oil level is above the center barrier. The moving contacts are carried on bridging yokes which move on wooden rods fastened to the barrier. At the porcelain column is mounted the operating mechanism, which moves all eight contacts at once. On opening, a spring-actuated piston puts pressure on the lower half of the cylinder. Oil is forced into the gaps and carries gas and oil through the arc and

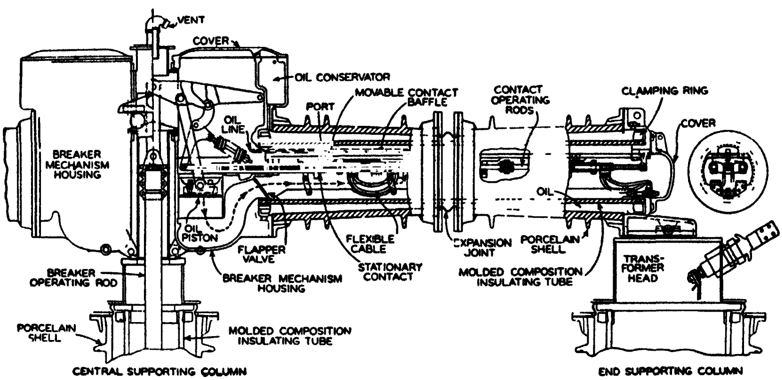


FIG. 159.—Cross section of one element of Boulder Dam impulse oil circuit breaker. City of Los Angeles, Department of Water and Power. (*Courtesy of General Electric Co.*)

out the ports into the oil volume above the horizontal barrier. One new feature of this device which has not been previously mentioned is the externally created pressure. The piston-supplied pressure gives rise to the name "impulse" breaker. Dielectric-strength recovery rates up to 5,200 volts per microsec. are obtained.

Static shields are mounted on the ends of horizontal tubes to create the desired potential gradient. In the multibreak Deion breaker for Boulder Dam, the same result is obtained by the use of an insulating tube with molded-in metal layers.

Some advantages claimed for the impulse breaker described, resulting from the reduction in oil volume to one-tenth that of a conventional breaker, are

1. Reduction in fire hazard.
2. Reduction in oil cost.
3. Reduction in total weight.

4. Ease of inspection and repair.
5. Shorter time to drain and refill.

GAS-BLAST CIRCUIT BREAKER.—Another modification of the blast principle that depends on the action of both oil and gas is the "expulsion" breaker[1] (Fig. 160).

In this structure the oil volume is smaller than in the explosion-chamber type, and it is claimed that the required motion of oil is therefore easier to obtain. On opening, gas from the arc expels a slug of oil carrying with it a stream of gas, an action similar to that of an expulsion fuse (hence the name). The arc is transferred to the arcing tip at one side of the center line of moving contact travel and adjacent to the vent. As the contact is withdrawn, the gas stream traverses the arc stream and extinguishes it.

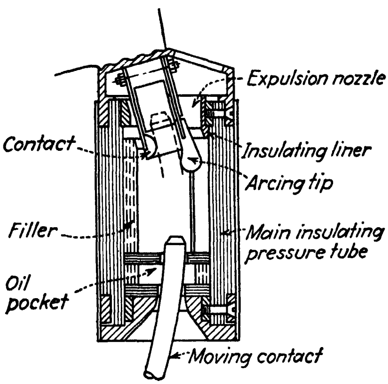


FIG. 160.—Expulsion oil circuit-breaker chamber. (*Schwager.*)

Structural Parts.—The locations of insulating structural parts in an oil circuit breaker can be listed as follows:

1. Tank barriers, lining, and insulation if ungrounded.
2. Moving-contact operation (lift rod).
3. Oil.
4. Bushings.
5. Accessories (closing solenoid, trip coil, relays, contactors, current transformer).

TANK.—The tank of a circuit breaker bears an important relation to insulation of such apparatus. Such features of tank design as shape, insulation clearances, oil depth, and bushing mounting are parts of the problem. The chief purpose of tanks is to contain the oil in which the contacts are immersed and in which the circuit is interrupted. The tank also acts as a dissipator for the heat developed in the oil, due to normal conduction and to arcs. The width of tank is determined by the distance between contacts and the desired clearance from contacts to

[1] SCHWAGER, *op. cit.*

ground potential. Length of stroke, height of oil over contacts, and required clearance from open position of contacts to the tank bottom determine the height.

Service requirements usually govern the tank shape. Rectangular tanks are built for small breakers of moderate interrupting capacity. All poles may be in one tank, or there may be one pole per tank. An upper limit of 2,500 amp. at 15,000 volts may be accepted for this type. In the medium-capacity class, we find an

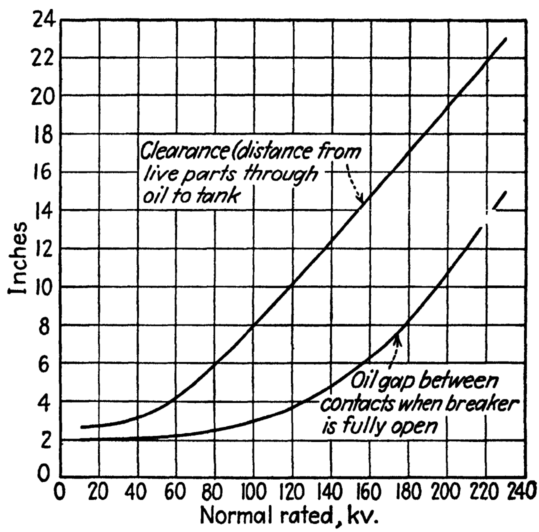


FIG. 161.—Conventional oil circuit-breaker spacing.

elliptical tank favored because of the increased strength in resisting high internal pressures. Such construction will cover ratings up to 10,000 amp. at 15,000 volts, four times the rating of the rectangular tank. As we approach a circular tank (axes of ellipse nearer equal), we gain in possible strength, so that practically all large-capacity breakers are built with round tanks. Even some low-voltage breakers for heavy current use a round tank, with all three poles in the same tank.

Especially with high-voltage circuit breakers, it may seem that tanks are excessive in dimensions and that the oil distance to the tanks from contacts is far greater than oil-breakdown tests would require. During interruption, however, large volumes of conducting gas may be formed which effectively reduce the oil-

clearance distance. As a further protection, most tanks (below 69 kv.) are fitted with insulating liners made of formed laminated tubing with Bakelite resin bond. If all poles are to be mounted in one tank, insulating partitions of the same material are inserted.

The proper oil clearance (shortest distance from terminals to tank) depends on the interrupting capacity of the breaker, whether for outdoor or indoor service, and other factors; so that,

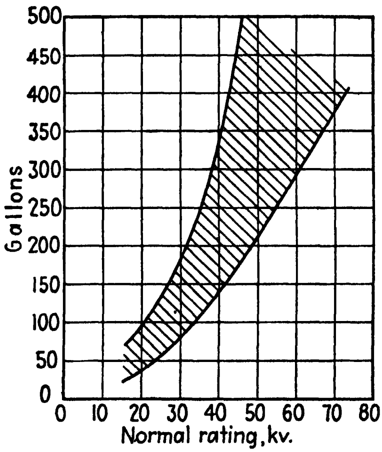


FIG. 162.—Oil volume in medium voltage conventional oil circuit-breaker tanks (three poles).

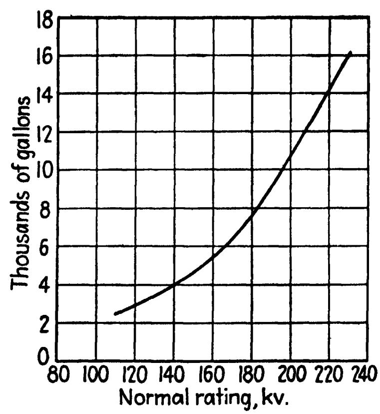


FIG. 163.—Oil volume in high-voltage conventional circuit-breaker tanks (three poles).

for any voltage class (115 kv., for example), practice does not dictate a definite clearance. An approximation to commonly used dimensions may be roughly represented by the curves in Fig. 161, giving also the gap between contacts when the breaker is open. These distances may be varied over a wide range to meet special conditions, but the curves represent safe average values. The curves in Figs. 162 and 163 similarly show approximate total oil volume for three poles for outdoor breakers of conventional design.

MOVING CONTACTS.—The moving contacts, which are often mounted on a metal crossbar, are operated by an insulated member, sometimes known as a "lift rod," since in most designs the contacts move upward to close. Probably the commonest material for this rod is wood, chiefly second-growth hickory, which is

strong and tough. The mechanical duty incident to closing and opening puts an enormous strain on this part, and the design is usually more difficult mechanically than electrically. One element of the problem is a means of fastening to the wood rod so that the full strength of the wood cross section can be developed. One form of joint is a malleable cap swaged over an inverted-cone end on the wood stick. If a cylindrical clamp is used, a long "bearing surface" for gripping is essential. It is obvious that the use of bolts through the wood may weaken the section excessively.

For heavy duty, multiple wood rods may be used, or some stronger material substituted. One effective scheme is to build up a laminated stick from Bakelite-impregnated wood veneer (Fig. 150). The laminations may be molded to a round shape or as a rectangular bar. Here again the method of attaching fittings is important.

Oil.—Insulating oil similar to that used in transformers has been the accepted liquid dielectric for circuit breakers. Extensive experimentation in Europe and the United States has been in progress on other liquids, particularly water, plain or with chemical additions. The objectives of such a search are a fireproof liquid that may have better arc-rupturing properties. Arcs can be interrupted successfully in water (some units are installed commercially in Germany), but the contacts must be subsequently withdrawn from the water because of the high conductivity of water. Fireproof liquids such as carbon tetrachloride and more recent chlorinated substances have not been successful. One reason has been the evolution of harmful by-products of arc action; another, the high cost.

The requirements for oil for circuit-breaker purposes are somewhat different from those for oil for transformers. Fortunately, the same oil will satisfy both purposes. For circuit interruption, the features should be

1. High dielectric strength.
2. Freedom from inorganic acid, alkali, or free sulphur.
3. Low viscosity (to aid in arc cooling).
4. Low freezing point (fluid at outdoor operating temperatures).
5. Resistance to emulsion (accidental water will separate from oil; also, carbon from arcs will settle out).

6. Desired specific gravity (ice from water should not rise through oil and float).

Further description of insulating oil will be found in Chap. IV, Insulating Materials.

BUSHINGS.—Bushings are required in the normal design of top-connected oil circuit breakers to insulate from the metal top the copper stud that supports the stationary contacts and carries the current to these contacts. These terminal bushings range in voltage requirements from 4.5 to 230 kv. or higher and range in current from about 200 amp. to about 6,000 amp. Different types of bushings are used for different conditions. Up to 23 kv. for small amounts of power, the porcelain bushing can usually be employed; for higher voltages, either oil-filled or condenser bushings are used.

Porcelain Bushings.—This type of bushing is used chiefly for the cheaper, moderate voltage breakers of relatively small rupturing capacities where the repulsion effects on the bushings, due to short circuits within the capacity of the breaker, are relatively small and porcelain bushings will have sufficient mechanical strength for the service. The smaller bushings usually have smooth sides; the larger porcelains are corrugated or provided with petticoats to increase creepage distances.

The porcelain bushings for low-voltage breakers are made in several different forms. Even for voltages of 23 kv. or less, on large power systems with severe short-circuit stresses, porcelain bushings are often unsatisfactory owing to their lack of mechanical strength. Thus, the condenser type or other constructions avoiding the use of porcelain alone is greatly to be preferred.

Oil-filled Bushings.—This type of bushing is used on the higher voltage breakers. The oil-filled bushing consists in general of a metal tube at the center and a series of short insulating cylinders separated by radial disks to increase creepage distance. These cylinders and disks taper gradually from the flange toward the end. Oil is admitted through the top of a visual gauge at the top of the bushing and can be removed through the oil drain at the bottom. An air-breathing tube allows for the expansion of the oil in the bushing and in the oil gauge itself. Lifting lugs are provided to facilitate handling the bushings. For outdoor service, the outer upper portion of the bushing is a one-piece porcelain rain shed, and a corrugated arc shield is used on the

lower end under oil. A standard design with some modifications is utilized as a terminal for transformers, oil circuit breakers, and cables. The insulation of these bushings is dependent on the oil, which has high insulating qualities and which by its circulation helps keep the bushing cool.

Condenser Bushings.—Bushings of this type are used for high-voltage oil circuit breakers, and many moderate voltage breakers having rated rupturing capacities of 90,000 kva. or over.

The condenser bushing design is based on the principle that the voltage across a group of condensers in series is inversely proportional to the capacity of the condensers, so that, with a number of condensers of equal capacitance in series, the voltage will be divided into an equal number of steps. Equal capacitance can be obtained by varying the spacing between concentric condensers or by varying the length, the radial spacing being kept constant. The latter is the common method. By proper design, based on this principle, condenser bushings have a fairly uniform fall of potential from the conductor to the tank cover and uniform creepage gradient along the surface. A design theoretically correct would result in a logarithmic profile that would be too thin and fragile at the ends. A practical compromise, sacrificing a little of the perfect-gradient idea, gives a better mechanical structure. The condenser is made by rolling, pressing, and baking onto a conductor, alternate layers of shellacked paper and metal foil (lead, aluminum, or copper). The bushing is thus made up of concentric cylinders of insulation with a layer of metal foil between them. The area of the foil and the thickness of the cylinders are controlled to give suitable capacities and voltage drops from the center to the surface. After the paper and foil have built up to the proper size on the condenser bushings for the high voltages, each cylinder is machined to accurate length, and thus both ends are given a taper. The assembly is then given a varnish and baking treatment. The largest section is provided with a metal band by wrapping with wire which furnishes a metal seat for the mounting flange.

Condenser bushings are usually designed with one condenser for about each 6,000 volts of line voltage, so that, for 92 kv., the bushing has 15 steps. In winding these bushings, paper is used with a thickness of 0.0025 or 0.0035 in., and the minimum thickness of insulation between foil layers is approximately

0.10 in. The lower voltage bushings are not tapered, but the foil is cut to calculated length and inserted at the proper place, although all layers of the shellacked paper are allowed to come out to the over-all length of the tube.

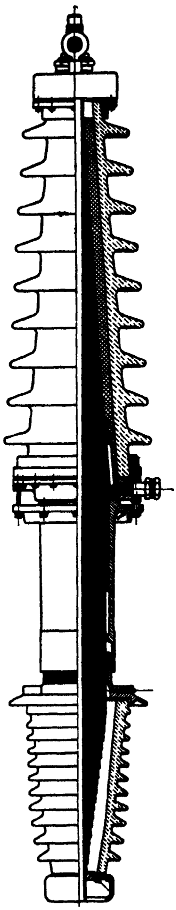


FIG. 164.—Condenser bushing for oil circuit breaker. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

To provide suitable protection to the bushings, casings are furnished at one or both ends. For indoor service, the air end of bushings of 115 kv. or over generally carries a cylindrical insulating casing, the space between the casing and the tapered portion being filled with an insulating compound which is plastic at operating temperatures, or with oil. A static shield at the ends of the casing minimizes corona and increases the flashover voltage. For outdoor service, a porcelain weather casing having a series of rain sheds is used. The weather casing for lower voltages is a single porcelain shell; on the 230 kv., there are two shells bolted together. The lower end of the bushing of the higher voltage breakers (154 kv. and above) is protected by a deep corrugated prefilled arc shield (Fig. 147). The purpose of this is to prevent carbon or impurities from collecting on the steps of the bushing and short-circuiting the condenser sections. Figure 164 is a cross section of a typical condenser bushing with the part outside the tank covered with a weather casing of porcelain. The space between the bushing and the casing is filled with insulating compound.

CURRENT TRANSFORMERS AND POTENTIAL TAPS.—In all high-voltage breakers, space is provided for mounting bushing-type current transformers. In many cases, these transformers are provided with five different taps, and thus 10 ratio combinations are possible. They are mounted within the main breaker chamber and are entirely enclosed in individual compartments to afford ample protection against damage under heavy interrupting duties.

The copper conductor inside the bushing forms the primary winding. The secondary winding and the iron constitute the bushing-type transformer. The leads of the transformers are brought outside so that connections can be made without lowering the tanks. For metering purposes on the lower current ratings (usually below 600 amp.), hipernik-core transformers give greater accuracy.

The secondary turns are wound over a stack of ring punchings and layers of tape applied to the outside. Varnish impregnation and baking are used for a finish and protection.

Because of the voltage gradient provided by condenser bushings, it is possible to make a connection between the last metal foil (the one nearest the ground) and the tank and secure economically a reliable potential for use in operating synchroscopes for synchronizing purposes and for operating certain relays. The potential obtained is about 4,000 volts, which is stepped down by a potential transformer to a suitable value. In addition, a spark-gap type of lightning arrester is used, and a capacitor and reactor to bring the potential in phase with the line. This complete device, usually called a "network-potential" device, is relatively inexpensive compared with high-voltage potential transformers.

A similar potential network is used with oil-filled bushings by adding an intermediate insulating tube concentric with the conductor inside the weather casing. A tap is brought out from a layer of foil on this tube to supply power to the network.

ACCESSORIES.—Oil circuit breakers are usually operated through mechanisms located on top of the breaker tank or at a distance. Among the electrical devices in common use are closing solenoids, trip coils, contactors, and relays of various types. Since these auxiliaries are control devices and are insulated like other similar apparatus, the reader is referred to the discussion of contactors, relays, and control devices in Chap. VII, page 188.

CHAPTER XI

TRANSMISSION-LINE INSULATORS

An insulator can be considered as an electrical device for the simultaneous mechanical support and electrical insulation of transmission and distribution apparatus. Transmission lines, bus structures, and disconnecting switches are examples of applications where insulation is found as a piece of equipment rather than as a material of construction. Five general types of insulators are recognized, using, incidentally, four kinds of insulating material.

Types	Materials
1. Pin type.	1. Porcelain.
2. Suspension type.	2. Glass.
3. Line post.	3. Molded composition.
4. Apparatus type.	4. Wood.
5. Strain type.	

Types. PIN-TYPE INSULATORS.—The name "pin type" derives from the method of mechanical support. The pin, which may be either of wood or of metal, is fastened upright on the pole crossarm, which in turn may be either wood or metal. The choice of pin material depends on prevailing atmospheric conditions and the method of circuit grounding. Metal pins are now in most common use, even with wood crossarms. Leakage in wet weather and corona may erode or even burn a wood pin. The upper end of the pin is threaded to engage a threaded hole in the porcelain. This hole may be bare porcelain; more frequently, it contains a cemented metal thimble for making a better joint and contact with the pin. The porcelain may be a single piece or be made of several nested "shells" cemented together to provide sufficient thickness of porcelain and creepage surface distance. The top of the porcelain has a groove across the diameter and a circumferential groove just below the top surface. The line conductor is laid in the straight groove and held in place by a tie

wire in the circular groove. Figure 165 shows the usual construction of a single-part low-voltage unit and a multished high-voltage unit.

The shape of the porcelain sheds, the number of corrugations on the underside, and total contour have all been developed after years of investigation and trial. Theoretically, a series of surfaces following equipotential surfaces and designed to prevent flux concentration is the goal. Practically, the electrical ideals

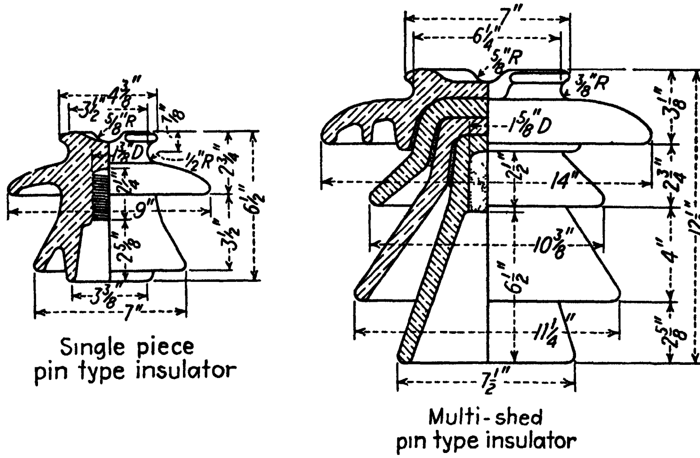


FIG. 165.—Pin-type insulators. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

have to be modified to meet several other requirements. First of all, the design must be capable of being manufactured economically. Next, the mechanical properties of the design are very important. For example, ruggedness of sheds is necessary, so as to be small-boy-with-rifle proof. The electrical-stress distribution, which may be nicely explored or calculated for dry conditions, will be completely changed when the unit is wet. Steep wave-front surges will affect behavior differently from normal frequency conditions. Consequently, any design is usually a compromise.

Pin-type insulators are sometimes used up to 70 kv. service but more frequently only up to 45 or 55 kv. Above this, suspension units are more common and cost less. The advantages of pin-type units are rigidity, the close spacing of lines possible (no swinging together as with suspension type), and ease of installation.

SUSPENSION-TYPE INSULATORS. *Cap and Pin.*—The form that has become practically universal is known as the "cap and pin." In this construction (see Fig. 166), a porcelain shell is provided with a dome to which is cemented a dome-shaped metal cap ending in a fastening device, usually a clevis or a socket joint. The inside of the dome has cemented into it a pin extending below the shed and terminating in a portion that fits the clevis of another cap, or a bulbous end that fits the socket of another cap. By

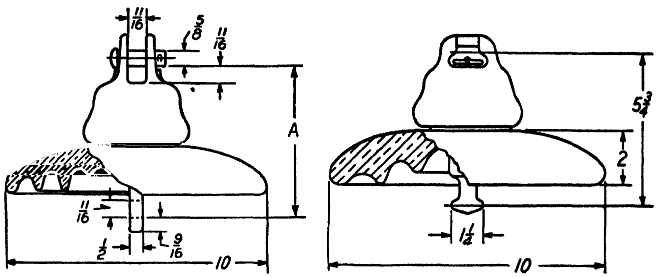


FIG. 166.—Suspension-type insulators. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

this means, any number of units may be connected in a string of the desired length. The cement is usually a Portland cement selected for minimum volume change, sometimes with a portion of silica aggregate. In this design, it will be noted that the porcelain is loaded partly in compression and partly in shear. To distribute stress and make a firm bond, the head (dome part) of the porcelain is coated on the straight portion with crushed porcelain or quartz glazed to the porcelain and known as a "sand band." Another important design feature is the resilient coating on top of the head, to allow for thermal expansion and contraction of the cap. Many specially shaped pins have been tried, some with ridges, successive cones, etc. But the most satisfactory form mechanically seems to be the simplest: a single curved cone shape merging into a straight shank, something like a pestle used for grinding chemicals. All hardware in contact with cement is coated with a thin layer of resilient material; this is first of all a cushion and second a lubricant which permits sufficient sliding to relieve stress concentrations.

The standard design is 10 in. in diameter, arranged to assemble with 5¾ in. distance between successive pins and exhibiting a nominal strength in tension of 15,000 lb. total. Other sizes, such

as 10½ in. diameter and 12 in. diameter, are available, and also units with extra creepage surface for foggy locations (Fig. 167). Heavy-duty units with strengths up to 30,000 lb. are installed in special locations such as angles of lines or on long spans.

Link Type.—Historically the Hewlett, or link-type, insulator is of interest. It consists (see Fig. 168) of a disk of porcelain with two holes through it at right angles to each other. Metal links inserted in the holes and connected together serve to form a chain or "string" of units. The porcelain is in compression between the links. This type called forth many clever devices for fastening, but it is very little used now. The difficulty of fastening, especially up on a tower, is a handicap. Another trouble is the concentration of compressive load on a small area of porcelain. Braided cables instead of solid links have been tried as a solution to this problem. Electrically there is a further disadvantage. The intrinsic capacitance of such units is low because of small metal "electrodes," and this leads to a poor potential distribution in long strings. This will be discussed later.

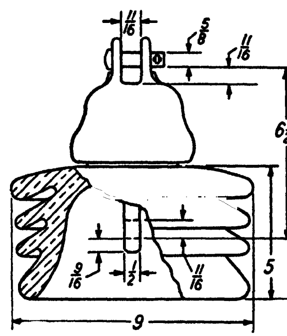


Fig. 167.—Fog-type suspension insulator. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Jeffrey-Dewitt Type.—A different form of construction that has been used with success consists of a heavy, rugged disk of porce-

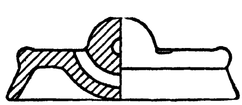


Fig. 168.—Link-type suspension insulator.

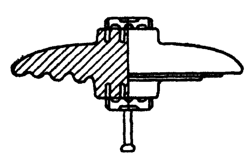


Fig. 169.—Jeffrey-Dewitt suspension insulator.

lain with a projection or boss on top and bottom (see Fig. 169). Several holes are made around a circle in each projection, into which a spider-shaped socket and pin are fastened with molten metal. This form of construction is simple, inexpensive, and very hard to damage mechanically. In this type the use of a metal alloy instead of Portland cement requires a different treatment of

the problem of mechanical stress to avoid plastic flow of the metal, not present with the more friable cement. The metal possesses the advantage that failure on overstress will not be sudden.

Smith Type.—An interesting development with which the author was connected was the form proposed by the late Prof. H. B. Smith of Worcester Polytechnic Institute in 1923. An attempt was made to create a rational design with respect to dielectric fields. It was found that air breakdown between one torus and another (if the minor diameters were suitable) approached the theoretical maximum of 30 kv. maximum per cm. If an insulating mechanical member could be inserted in the center hole of the tori without disturbing the electric field, an almost ideal insulator would result (see Fig. 170). After much experimentation a form was devised that gave very high flashover. But disappointing performance in rain (which ran down the central stick and caused failure) emphasized the importance of adverse service conditions —rain, dirt, fog, etc. The final shape consisted of a large metal "umbrella" with rolled edge, a central insulating "stick," and a lower torus, or "doughnut." Several of these were put on service test but were ultimately abandoned because of the limitations of available materials. A weatherproof strong center stick seemed to be out of reach. This brings to mind the experience in so many insulating problems. First of all, we are frequently hampered by the limitations of available materials. Further, a theoretical approach to a problem is often ruined by abnormal service conditions for which calculation is futile. Only bitter experience can be used as a guide. A story is told of a young designer who calculated to a nicety the stresses in a certain shaft of a locomotive and figured the theoretically proper diameter. The chief engineer looked at the drawing dimensions and without looking

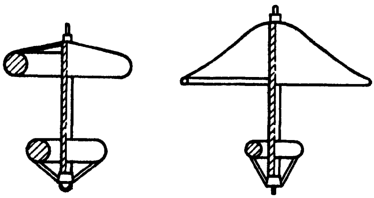


FIG. 170.—Smith suspension insulator.

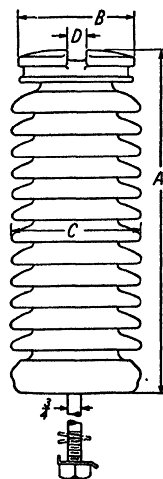


FIG. 171.—Line-post insulator. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

at the calculations said, "Make that shaft one-half inch bigger, and it will be O.K." Calculation counted little in the face of experience.

LINE-POST INSULATORS.—A new form has appeared in the last few years that possesses certain advantages. The line post (see Fig. 171) is essentially a hollow porcelain column closed at the top end and having a corrugated outer surface. A metal cap is cemented to the bottom end for fastening the insulator to the crossarm. The top has the usual grooves for the line and tie wires. Mechanically this unit has excellent strength and ruggedness. Electrically it has the advantage of low unit stress, long creepage path, and, most important, low radio interference.

APPARATUS-TYPE INSULATORS.—The name comes, not from the construction, as with pin type and suspension type, but from the application. Apparatus insulators, formerly called "post insulators," are similar in shape to pin-type units and are used singly or in columns to support switches, reactors, lightning arresters, and other station apparatus usually placed outdoors (Fig. 172). The head of these insulators is fitted with a large metal cap provided with boltholes for fastening to the next unit or to the mounted apparatus. The sheds and pin are larger and

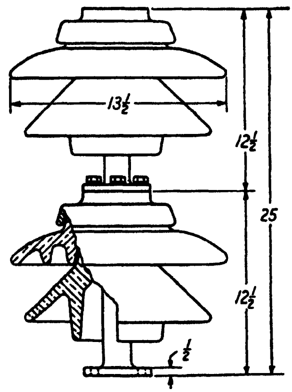


FIG. 172.—Apparatus-type insulators. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

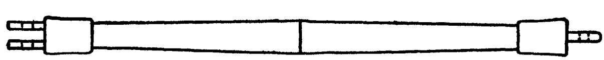


FIG. 173.—Wood strain insulator.

more rugged than in pin-type units for the same voltage. This ensures adequate cantilever strength in a column of units. Where extreme column strength is required, three columns may be arranged in a triangle and rigidly connected by plates at top or bottom or at any level desired.

STRAIN-TYPE INSULATORS.—Wood strain insulators, already referred to, consist of hickory sticks with hardware swaged to the conical ends (see Fig. 173). Length may vary according to

voltage service from 6 in. for 500 volts to 6 ft. for 22,000-volt trolley wires.

The usual form of porcelain strain insulator is a link type, sometimes called a "strain ball." Two holes at right angles link each other, and the guy wires or cables are threaded through the holes (Fig. 174). The most frequent use is for guying towers or poles. It is not expected that the upper end of the guy wire will be "live," but it might be in wet weather or if line insulators fail. The strain insulator prevents accidental energizing of the wire that goes to the ground level, where it might be touched.

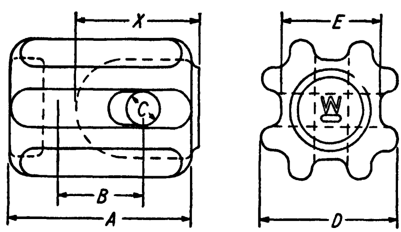


FIG. 174.—Porcelain strain-ball insulator. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Another form of strain insulator for higher voltage is made exactly like a miniature suspension insulator, 6 in. in diameter.

Materials.—PORCELAIN is used for all five shape types of insulators and is the most common material. In spite of its mechanical vulnerability and relative weakness in tensile strength (3,000 to 6,000 lb. per sq. in.), it has many virtues such as high and permanent dielectric strength, resistance to weather, and adaptability to desired design shape. It is very strong in compression (40,000 to 80,000 lb. per sq. in.), resists shearing stresses, and has good performance under heat and cold shock. Atmospheric effects on the surface of porcelain are imperceptible, and dirt does not become embedded.

GLASS is used to a limited extent for line and apparatus insulators, being pressed into molds of the desired shape. It has an advantage in uniformity of composition but may suffer from nonhomogeneity of structure, so that internal strains may exist without visible evidence. Visible defects are readily detected in glass insulators, facilitating inspection. The surface of glass is not so resistant to atmospheric conditions as porcelain, since glass is somewhat soluble in water, especially if rain water is

contaminated by industrial atmospheric conditions. Brittleness in glass has been practically eliminated, and the heat shock resistance is satisfactory. One advantage glass possesses is that it is a poor target for hunters and small boys to shoot at.

Suspension-insulator Strings.—For high-transmission voltages, the lines are suspended from the towers by long strings of the suspension insulators already described. The number of

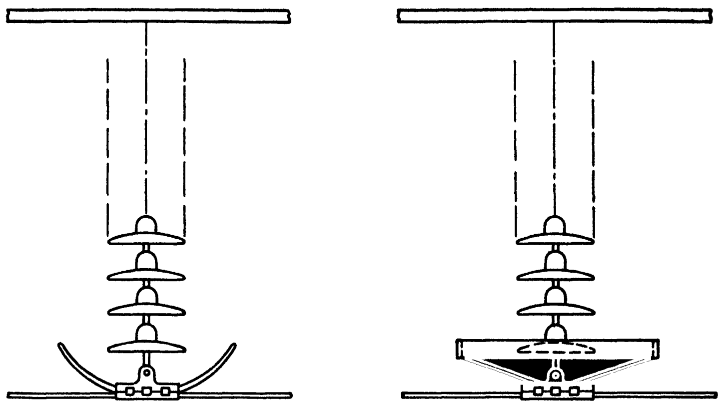


FIG. 175.—Suspension insulator strings with protective devices.

units used for any line voltage is not always the same. The type of service required, location geographically, weather conditions, special adverse atmospheric conditions, altitude, method of grounding, and other factors all have to be considered. For a rough approximation, 10 to 15 kv. nominal line voltage per unit may be used. Thus, for 115-kv. service, 7 to 10 units may be used. Of the two methods of attachment (ball and socket or clevis and pin) described, the clevis and pin is probably more widely preferred because it is a little easier to assemble.

Many insulator strings are provided with extra devices at the bottom (line end) or top (ground end) or both. These take the form of horns, rings, shields, etc., which are applied for two reasons (Fig. 175). The earliest reason was the improvement in voltage distribution (electric loading) along the string. The other and more recent reason is protection of the string from the destructive effects of flashover. During adverse weather conditions or lightning surges, flashover may occur. Normally the

path would be over the insulator surfaces, and breakage might result. If a weaker dielectric path is provided between metal electrodes away from the insulators, a flashover will cause no damage.

The potential distribution, chiefly important under dry conditions, is determined largely by capacity relations. Under wet conditions, surface resistance rules, and the distribution is usually

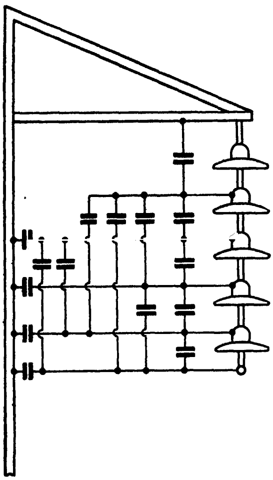


FIG. 176.—Capacitance relations of a suspension string.

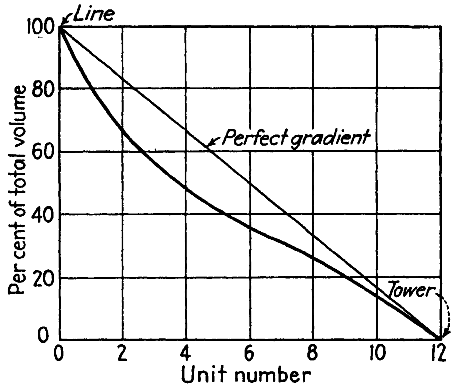


FIG. 177.—Potential distribution of suspension insulator string of 12 standard units.

more or less uniform. An insulator string may be represented electrically by a capacity network (Fig. 176). Each unit has a capacitance to ground and to every other unit. The result of this condition is a piling up of voltage on the line unit (bottom) compared with the ground unit. This means that the upper units are not sharing the voltage duty desired and are ineffectively used. Figures 177 and 178 show typical voltage distribution curves of uncorrected strings. There are several methods of correcting this condition. One is to increase the capacitance of each unit so that it will be large compared with the capacitance of its hardware to other objects. This was done at one time by increasing the size and area of the hardware (cap and pin). A refinement of this method would be to have several designs of increasing capacitance and to assemble a graded string therewith, which would involve keeping several kinds of insulators on hand.

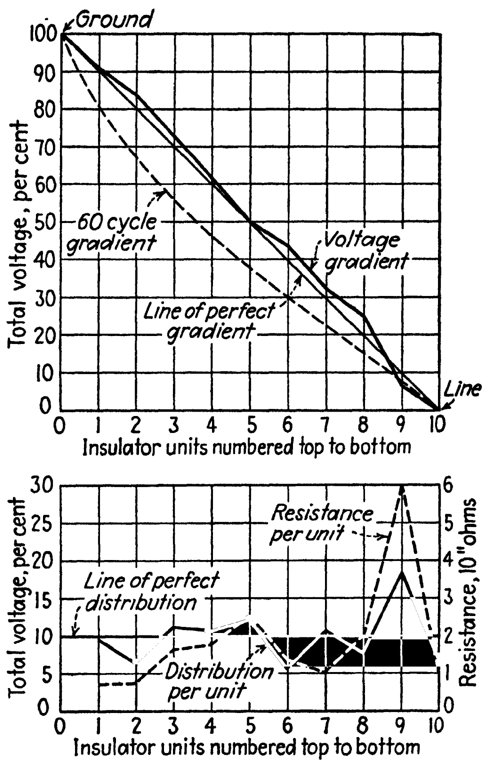


FIG. 178.—Direct-current potential distribution of string of 10 standard suspension insulators. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

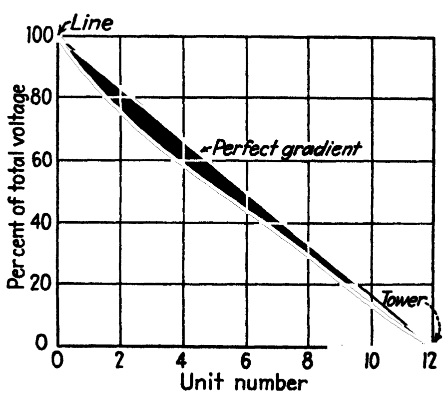


FIG. 179.—Potential distribution of string of high-capacitance suspension insulators.

Another method is to add to the capacitance at the high-voltage end by using metal rings or shields or horns. The effects of these various corrective schemes are shown in Figs. 179, 180, and 181.

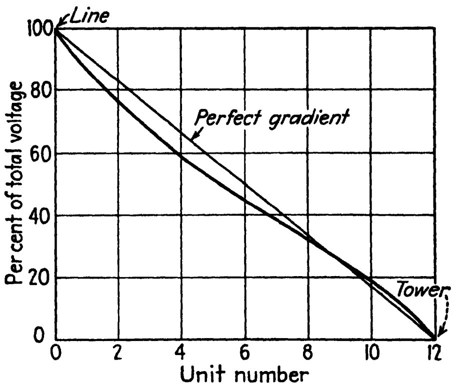


FIG. 180.—Potential distribution of string of standard suspension insulators with arcing ring.

In the design of individual insulators or the composite problem of strings or columns, a knowledge of the dielectric field is a useful tool. Exploring fields graphically, by indicating devices, or by calculation well repays the time spent when a new problem

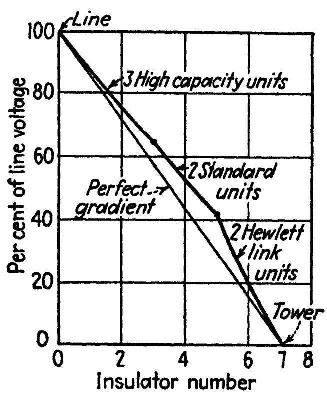


FIG. 181.—Potential distribution of string of suspension insulators of mixed types of varying capacitance.

is under study. Convenient methods are also available for quickly determining the percentage of voltage across any given unit in a group. These exploration and test methods will be described in Chap. XVII, Insulation Testing.

CHAPTER XII

LIGHTNING ARRESTERS

Function.—In some respects, a lightning arrester resembles a safety valve. A vessel containing gas or vapor (*e.g.*, steam) is usually equipped with a relief device which operates when pressure exceeds a predetermined margin above normal. The excess pressure is vented to prevent damage to equipment. Such a safety valve must fulfill another function to be acceptable: it must close when the emergency is over and not permit the total volume of gas to be released. The opening and the closing are both necessary functions. Present-day arresters have points in common with safety valves. They are electrical valves that pass transient surges but prevent the flow of normal frequency power through the same path. This selective action marks the effectiveness of a lightning arrester.

But the analogy should not be treated too rigorously; for in the case of gas or steam, the emergency state arises within the equipment, but in the electrical system the most frequent cause of the excess "pressure" comes from outside—lightning. Some surges are traceable to switching disturbances, but the chief reason for lightning arresters is the natural phenomenon giving the name to the device.

Comparing a fuse to a lightning arrester brings out a difference in function. A fuse is also a protective device functioning when *current flow is excessive* and acting to interrupt the current completely. A lightning arrester acts as an overvoltage device, operating when *electrical pressure is too high.* It does not, normally, interrupt the circuit but provides a by-pass for relief of excess pressure and removes the by-pass to restore the normal circuit when the transient pressure is over. Its function is to protect the insulation of electrical apparatus from failure that might ensue from excessive potentials.

Forms.—There are many specific forms of arresters available, all exhibiting the valve action. A description of the construction

of these valve materials and arrangements is not part of the present subject. Since arresters are essentially high-voltage equipment, there must be a problem in insulation which we may study. First, we note that arresters usually have series spark gaps which break down before the active elements function. In other words, the valve material is isolated from the power circuit until the series gaps become conducting from overpotential. Without these the elements would conduct current continuously,

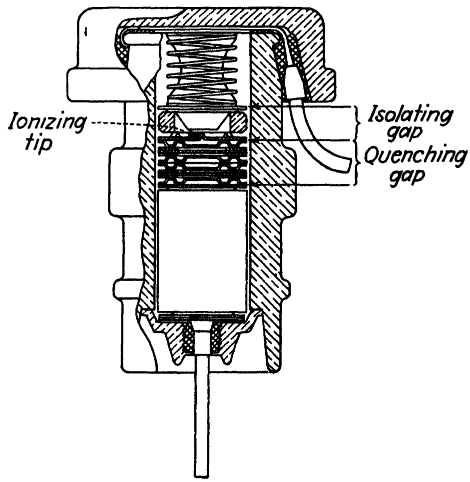


FIG. 182.—Three-thousand-volt "autovalve" lightning arrester. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

for they are made of ingredients that are high-resistance materials, rather than insulators. The second insulating part is the external protection to prevent flashover or creepage on the surface of the arrester parts. Discharge currents must be carried through the valve (disks, blocks, pellets, or crystals) and not over the surface. An insulating surface coating, such as waxes, and an insulating container (casing) therefore become necessary.

AUTOVALVE.—The Westinghouse "autovalve" arrester is an interesting illustration of the essential points and will be described as an example. We shall start with a low-voltage form and then see what modifications are added for higher voltage units. Figure 182 shows a 3,000-volt design.

The main casing is a cylindrical porcelain piece sealed at the top (after assembly of internal parts) by a spun-metal cap and a

porcelain-top cap over this and at the bottom by a porcelain piece glazed to the cylinder. The bottom porcelain is what is known as a "drop-out" cap and has a thin section near the outer edge. If a surge reaches the arrester that is far in excess of its capacity to relieve (such as a direct lightning stroke), the arrester element will fail and become hot. The heat developed will crack the bottom porcelain at the vulnerable section, causing it to drop away from the arrester, carrying also the ground lead and opening the circuit.

Gaps.—Above the arrester block is the gap structure, composed of two parts: a series, or isolating, gap and a "quench" gap.

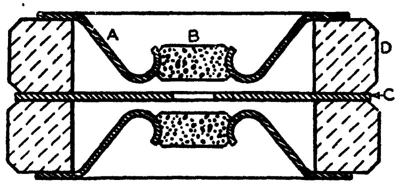


FIG. 183.—Series gap. (*Roman.*)

The series gap of Fig. 182 disconnects the arrester from the line when not discharging and has unsymmetrically shaped electrodes. The upper is a disk with three "bumps" at the edge, and the lower is a toroidal section. One requirement of the series gap is that it must break down (connecting the arrester elements to the line) at a voltage not too much in excess of normal line voltage (if adequate protection is to be given) and must do this uniformly. Many forms of spark gap, spheres, for example, are inclined to be erratic in behavior, and both the time lag of breakdown and the voltage necessary are not uniform from one operation to the next. Several methods are known for starting ionization of gaps. Ultraviolet light will help, but this could hardly be used for lightning arresters. Radium is effective in producing prompt and uniform ionization leading to gap breakdown. At one time radioactive materials were used in these series gaps to a limited extent. Points or concentrated "bumps" have the desired effect and are easy to provide. Ionization also seems "easier" if one electrode is of a different shape from the other. Another procedure for speeding up the series gap is to place a carborundum insert in the center of the toroidal section, which serves to initiate ionization at minute points on its surface (Fig. 183).

An additional gap, known as a "quench gap" (Fig. 184), is inserted next to the series gap and assists in interrupting the power current that starts to follow the surge discharge path. The arrester blocks are the principal elements in this function, but the capacity can be much extended by the use of quench gaps.

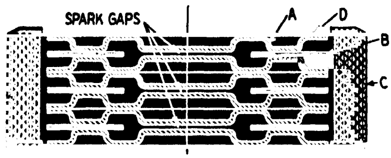


FIG. 184.—Quench gap. (*Roman.*)

An explanation of the combined action of the series and quench gaps in such an arrester as has been described is as follows: When a surge voltage occurs that is 1.5 to 1.75 times the normal rated

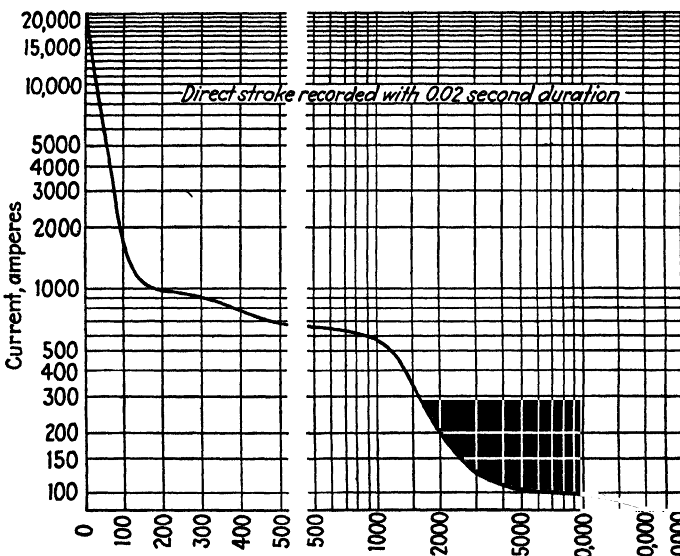


FIG. 185.—Current in lightning stroke. (*Wagner.*)

arrester voltage, the series gap breaks down. The total voltage is then applied to the arrester blocks, in series with the quench gaps (shunted by resistance rings). Mild disturbances of small energy may be relieved in this manner. If the voltage keeps rising, the quench gaps break down at 2.25 to 2.5 times the normal

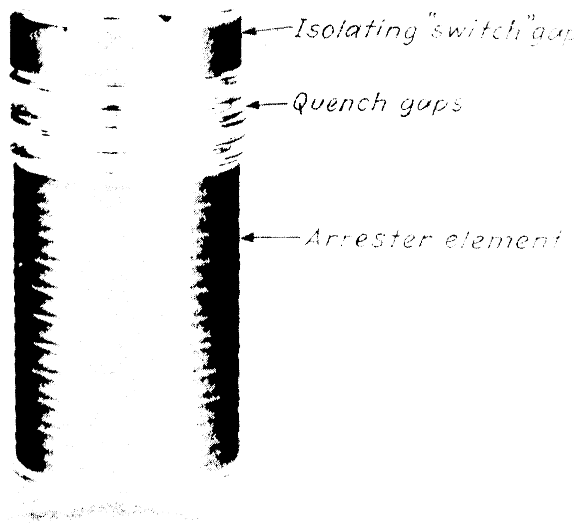


FIG. 186.—Parts of lightning arrester. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

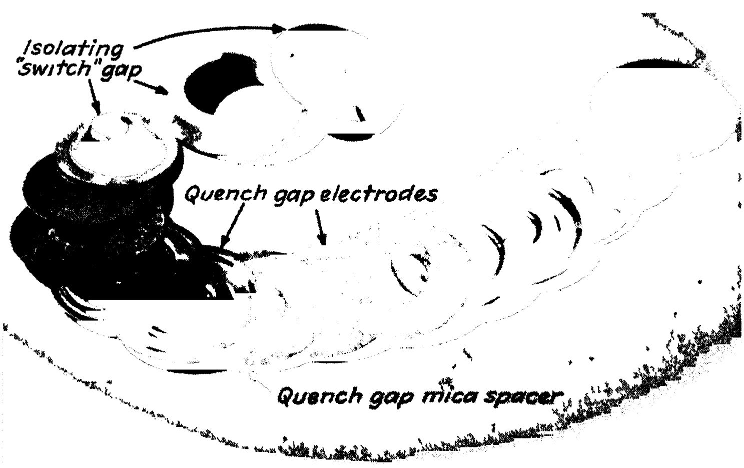


FIG. 187.—Gap parts of lightning arrester. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

volt crest. The surge is then discharged through the arrester blocks. Power current of a few amperes value will follow the surge and be interrupted by the quench gap, followed by extinction of the series-gap arc.

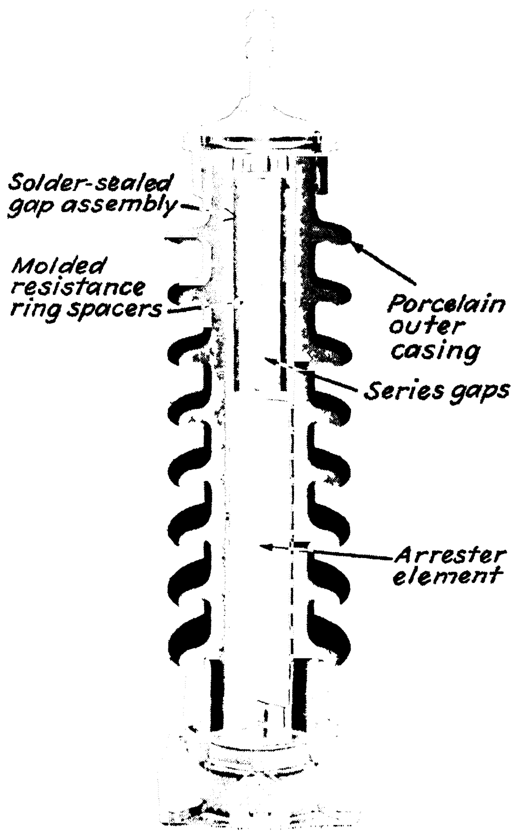


FIG. 188.—Section of 37-kv. lightning arrester. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

We have noted the probable mechanism by which the quench gap breaks down on surge. After it is conducting current and the excess voltage has disappeared, this gap transforms its action into one of current interruption, an interesting automatic phenomenon of great usefulness. The power current is extinguished at the zero point of the alternating-current wave through the

deionizing effect of the multiple metal electrodes, just as in the Deion types of circuit breakers.

HIGH-VOLTAGE ARRESTERS.—Field research in recent years has shown definitely that many lightning strokes have an initial high current discharge for a few microseconds, followed by a much

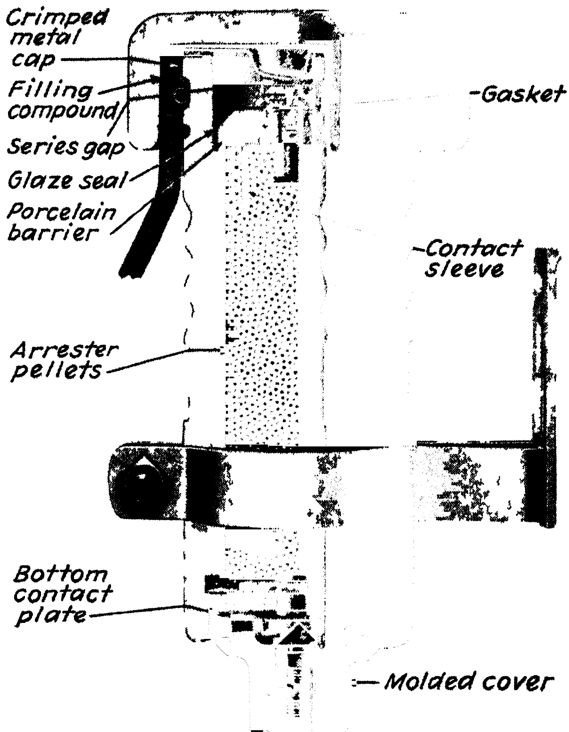


FIG. 189.—Pellet-type distribution voltage arrester. (*Courtesy of General Electric Co.*)

lower current which may last 1/50 sec. (Fig. 185). Arresters are now designed to be capable of relieving the first heavy current surge without failing from heating from the longer tail of the wave. High discharge-capacity elements combined with the quench gap present a satisfactory method of taking care of this double duty. The assembled parts, blocks with insulating coating, quench gap, and series gaps, are shown in Fig. 186. The quench gap consists of several pressed-brass electrodes separated

by mica washers and shunted by a ring of molded resistance material which produces a uniform gradient across the gap sections by fixation of the dielectric field external to the gaps (Fig. 187).

A quench gap has a low impulse ratio (surge-voltage breakdown vs. 60-cycle breakdown) which is a desirable feature for

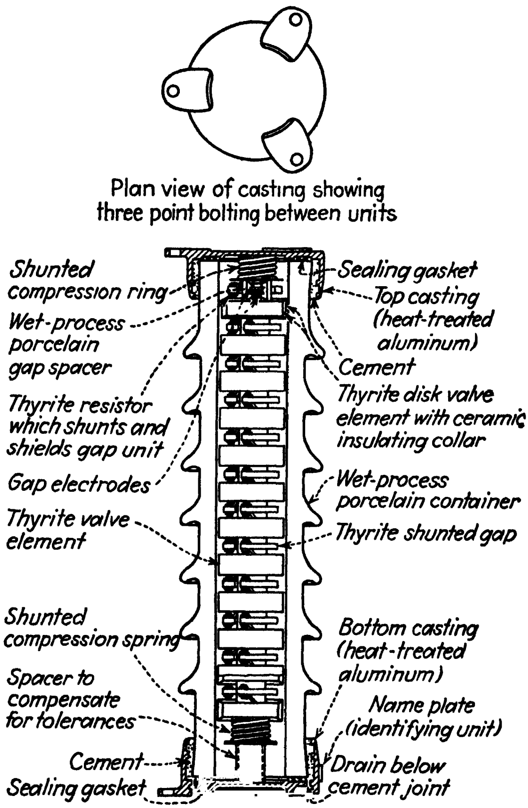


FIG. 190.—High-voltage Thyrite arrester. (*Courtesy of General Electric Co.*)

good surge protection. With the potential-distributing resistance spacer surrounding the gap, the impulse ratio can be made nearly unity. Without the shunting resistance, the ratio may be 2. The low impulse ratio of this type of gap may be attributed to the early formation (on voltage rise) of corona at the points of contact of the electrodes and the mica washers. With an abun-

dant supply of ions, this gap is more rapid in breaking down than many other shapes of electrode.

In general, higher voltage, higher discharge-capacity units are made by increasing the diameter of arrester elements, increasing the number of blocks in series, and adding more quench gaps with resistance spacers. At high voltage the points of stress and arrangement of parts to distribute stress and prevent internal flashover have to be carefully designed. For voltages higher than 73 kv. the arrester is built up of several similar sections. At the top of each section is the gap group consisting of several gaps in series, all encased, dried, and sealed in a separate porcelain tube. The rest of the section contains arrester blocks. A 37-kv. arrester is illustrated in Fig. 188.

Pellet Type.—The pellet type of arrester (General Electric Co.) for low distribution voltages contains pellets of valve material in a porcelain cylinder. The pellet column prevents power follow but allows surge discharge. A series gap at the top isolates the valve element from the line until it is broken down by a surge (see Fig. 189).

High-voltage Thyrite.—Another arrangement of arrester parts to ensure good potential distribution at high voltage is that shown in the Thyrite unit (Fig. 190). The arrester blocks are separated by series gaps around which are shunted horseshoe-shaped resistors made of the arrester material. This shunting resistor controls the voltage distribution across the individual gaps and fixes the potential of successive units in a stack so that sections may be assembled for higher voltages.

CHAPTER XIII

CAPACITORS

Requirements and Functions.—In nearly all electrical apparatus, insulation plays an auxiliary role, limiting the flow of current in metallic circuits to useful channels so that the desired combination of electromagnetic, mechanical, or thermal effects can be obtained. Thus considered, dielectrics are important parts, but not the principal functioning parts, of equipment.

Capacitors are the major exception to this statement. Here we have no complete metallic circuit, no moving parts, no magnetic path, only electrodes with a dielectric between. The chief tangible device around which electrostatic concepts are built and by means of which dielectric behavior is illustrated is the condenser. (The practical form of a condenser is now called a "capacitor.") In such a device the insulation is not an auxiliary, but the heart of the equipment. We are therefore concerned, as for no other electrical apparatus, except perhaps cables, with all the characteristic phenomena such as absorption, dielectric loss, power factor, even more than dielectric strength.

At normal power frequencies and distribution circuit voltages, the electrical engineer does not often meet problems of dielectric loss, power factor, or behavior of polar molecules. He is more worried about the life at excessive temperatures or the mechanical properties of the insulation he has chosen. But with capacitors, the more dielectric theory he knows how to apply, the better the product. And here the fundamental work of the physicists and chemists finds direct application. The size and cost of capacitors are dependent on the effectiveness with which the dielectric can be used, or the energy handled per unit volume. Transfer of heat (from internal losses) to the outside by water-cooled terminal edges will greatly increase the rating of a given volume of capacitor material. For example, a 230-kva. group for 1,250 volts, 2,000 cycles, can be obtained from 25 lb. of dielectric material by efficient removal of heat.

Dielectric.—A good capacitor must contain a dielectric whose electric strength is high, so that the thickness between electrodes can be a minimum; whose dielectric loss is low to reduce internal heating; and whose dielectric constant is high to reduce the area for a given capacitance. At first thought, a liquid dielectric of high dielectric constant might be suggested. There are two objections to a liquid alone: *viz.*, the problem of mechanically spacing

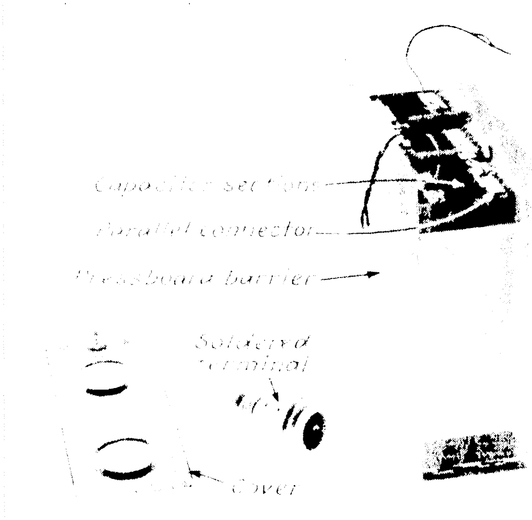


Fig. 191.—Capacitor assembly without tank. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

the electrodes, and the hazard of failure by lining up of conducting particles in the liquid. A laminar solid is preferable, and mica fulfills the requirements admirably, because of its low loss factor. Many small capacitors, particularly for high voltage, are made with mica sheets between conducting plates. On high voltage, air pockets must be eliminated by impregnation. Mica is not used for large capacitors because of the cost and the difficulty of obtaining thin mica sheets or built-up plate of satisfactory uniformity. Inherently, large sheets will have weak spots dielectrically. If several thin sheets are used to "stagger" the poor spots, the combined mica plate is too thick.

Construction.—Until recent years, the common capacitor used for power-factor correction or harmonic filtering was made of metal-foil electrodes with thin oil-impregnated paper as the

dielectric. A stack built of alternate layers of paper and metal foil will form a capacitor if alternate foil layers are connected in two groups of parallel electrodes. Construction of this type might be expensive, for the layers must register perfectly and be arranged with adequate creepage distance between foil layers. More preferable is the usual construction in which thin paper

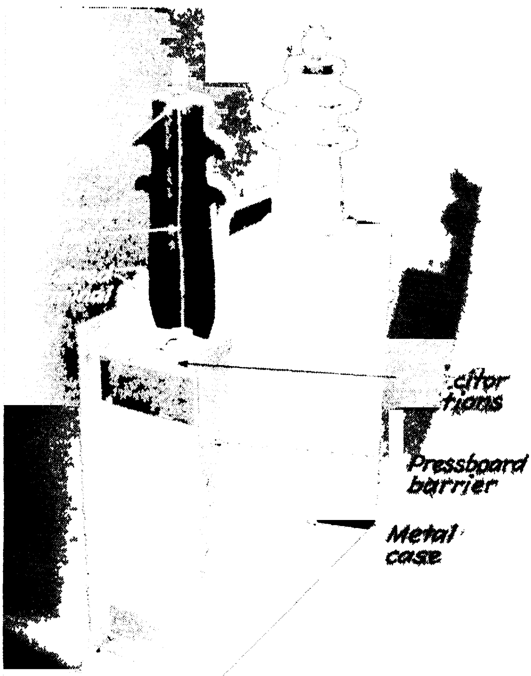


FIG 192 —Cutaway section of capacitor (*Courtesy of Westinghouse Electric & Manufacturing Co*)

from continuous rolls is wound as a sandwich between two metal foils also fed from rolls. The combination is wound on a mandrel a few inches in diameter until several layers are built up. The hollow cylinder of paper and foil is then removed from the mandrel and pressed flat. A complete capacitor may consist of several of these collapsed tubes packed together in a metal tank with terminals connected in series or parallel to tabs inserted in the foil layers (Figs. 191, 192). After assembly a thorough heating and vacuum drying is necessary to remove all traces of moisture and air before the tank is sealed (Figs. 193, 194). The

treating-out process, removing most of the moisture in 24 hr., is usually continued for several days for large capacitors, to ensure perfect dryness.

Development of oil-paper capacitors reached a point where very little improvement in working temperature, allowable volt-

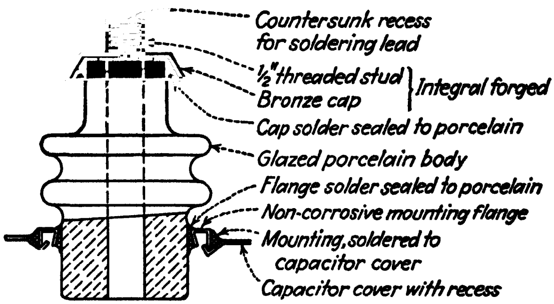


FIG. 193.—Solder-sealed capacitor terminal. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

age stress, and physical properties of the oil seemed possible except by increasing the voltage stress to a dangerous point and thereby decreasing the margin of safety between working and failure voltages. Study of the problems took two directions: (1) a search for better paper; (2) compounding a better dielec-

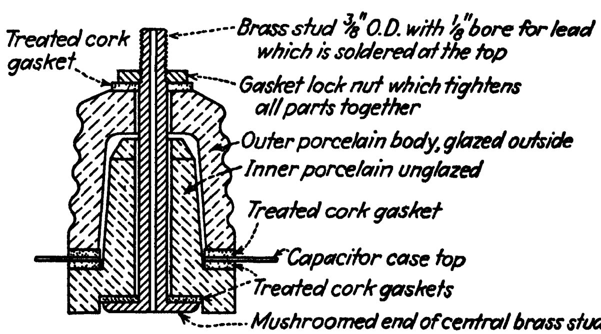


FIG. 194.—Gasket-sealed capacitor terminal.

tric. For many years a thin linen paper seemed the best obtainable, but later a thinner Kraft (wood-pulp) paper was developed, substantially free from the occasional defects of linen paper. Present capacitor paper for low-voltage applications is 0.00035 in. thick, an almost unbelievable accomplishment considering the dielectric and mechanical properties required. One layer of

a solid dielectric is more of a risk than two layers half as thick. With multiple layers the chance of bad spots lining up is remote. It is usual practice, for example, to use two or three layers of paper (total thickness about 0.001 in.) between layers of foil for 230-volt service. For higher voltages, as many as seven layers may be used, with paper thicker than 0.00035 in. where required.

Chlorinated Hydrocarbon Liquids.—The best liquid dielectric now available is a chlorinated hydrocarbon selected from a group of materials known as "aroclors," similar to one of the ingredients in the fireproof liquid used in transformers. Its dielectric constant is twice that of petroleum oil, the dielectric strength is 30 per cent higher, and its temperature characteristics are more favorable than oil. At low temperature, oil crystallizes and forms voids where corona may develop. The new liquid, called Pyranol, Inerteen, or Dykanol A by the three different suppliers, does not crystallize at low temperatures and will withstand higher temperatures without deterioration than oil.

The reason for the high dielectric constant of the aroclor liquid is that it is a polar material. It exhibits dielectric absorption and anomalous dispersion. Observation of the behavior of this polar liquid in capacitors is a splendid illustration of the application of dielectric knowledge and an adjustment of engineering design of the inherent properties, favorable and unfavorable.

TEMPERATURE EFFECTS.—At low temperatures, aroclor has no higher dielectric constant than oil, but somewhat below room temperature there is a region of anomalous dispersion in which the dielectric constant increases. This seems like a handicap that would be serious for capacitors operated outdoors in cold weather. The capacitance changes accordingly, and the loss increases over a narrow low-temperature range. How can these adverse characteristics be tolerated? Fortunately, the increase in loss that accompanies the change at low temperatures heats the capacitor sufficiently to bring it back to the optimum electrical properties, even with ambient temperatures as low as $-50°C$. This type of capacitor adjusts itself in time to the proper operating temperature; but such a device cannot be used on intermittent duty where the initial properties are important, as, for example, in capacitor motor starting at low temperatures.

BEHAVIOR OF POLAR DIELECTRIC.—Now, let us see what goes on in the polar dielectric. The behavior is shown graphically in

Fig. 195. Berberich[1] and Hill[2] explain that, at low temperatures, the material is too viscous for the permanent dipoles to rotate and the dielectric constant (being the same as oil in this state) is determined by the electronic polarization. The loss is also low. With rising temperature, the polar molecules rotate as the viscosity decreases until the maximum effect is reached. At this

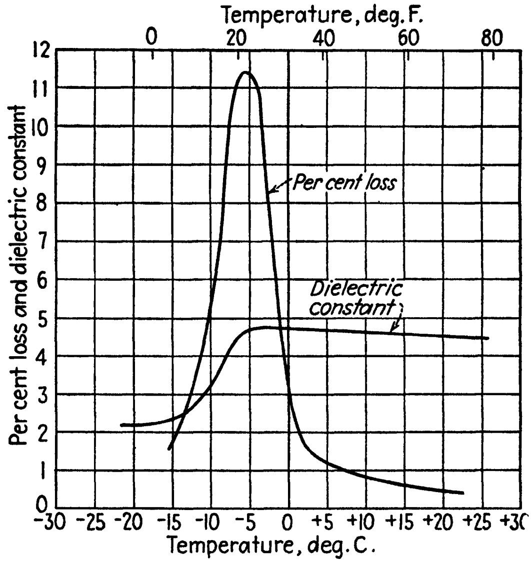


FIG. 195.—Initial dielectric loss and dielectric constant of chlorinated capacitor liquid at various temperatures. (*Hill.*)

point a very high maximum occurs in the power-factor curve (polar rotation producing loss thirty times the minimum stable value), and the dielectric constant rises rapidly to the maximum. These maxima occur when the natural period of the dipoles matches the circuit frequency. Beyond this point the thermal motion of molecules disturbs the orientation of the dipoles by exerting a restoring force, an effect that increases with rising temperature and accounts for the slow decrease in dielectric constant after the critical maximum is reached. The liquid to be

[1] "The Triple Alliance in Electrical Insulation," *Elec. Eng.*, vol. 59, p. 23, October, 1939.

[2] "Some Problems of Physics in the Application of Dielectrics as Insulators," *Jour. Applied Physics*, vol. 8, p. 606, 1937.

useful must then be selected so that this transformation occurs at a temperature below the usual operating value.

The effects of the polar dielectric on operation of a capacitor can be summarized in graphic form as the curves in Figs. 196,

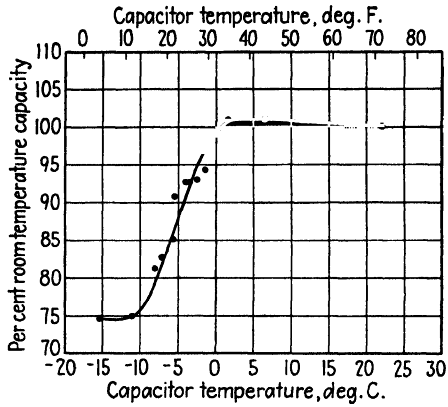


FIG. 196.—Initial capacitance of chlorinated liquid capacitor. (*Marbury.*)

197, and 198. The initial capacitance of a capacitor held at any ambient temperature is shown by Fig. 196. For the unit tested, the capacitance at $-15°$C. is thus 75 per cent of rating, is practically normal at 0°C., and nearly constant up to 25°C. Another

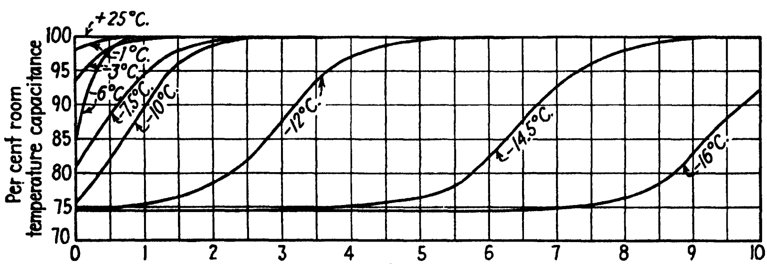


FIG. 197.—Change in capacitance with time, chlorinated liquid capacitors. (*Marbury.*)

limitation of this polar dielectric should be noted. On direct current, where no losses occur, the capacitance is determined by the ambient temperature; and if this is below the critical point, the capacitor will not raise its own temperature by dielectric losses. The unit at low temperature on direct current is therefore no higher in capacitance than an oil-filled unit.

When an aroclor capacitor is operating continuously at rated voltage and frequency, the normal energy loss is small but sufficient to keep the temperature at a point where the viscosity is in the range favorable for minimum loss due to polar rotation. The lower the ambient temperature, the more internal heat is developed, and therefore the losses may rise 50 per cent or more above the value at normal room temperature. The actual working temperature of the dielectric is rarely below 20°C. in usual designs.

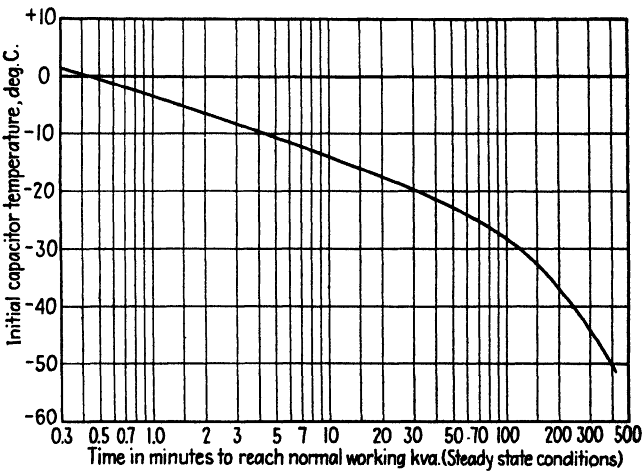


FIG. 198.—Capacitor kva., showing time required to reach normal after connecting to the line at various initial temperatures. (*Marbury.*)

The initial capacitance at any temperature is quite different from the steady state, which has been shown to be quite uniform. A transient therefore takes place, the curve shape of which depends on the initial starting temperature. The change from the curve in Fig. 196 to the steady state takes place according to the relations of the curve in Fig. 197. Another method of presenting these facts is illustrated by the curve in Fig. 198, showing the time required to reach normal output from various initial ambient conditions of the dielectric.

We have shown how a polar dielectric possesses certain very useful properties along with some adverse features. By proper recognition of the behavior, a practical design can be evolved which for alternating-current applications takes advantage of the good points and circumvents the handicaps.

CHAPTER XIV

HEATING APPLIANCES

Very little use can be made of organic insulation in heating devices. The choice narrows mainly to mica and heater-body porcelain, supplemented by ceramic cements and occasionally asbestos. In spite of the limited number of materials available, great variety is shown in the ingenious methods of application. Several ways of doing the same job can be devised, and many times the preferred design is determined by the element of manufacturing cost.

Insulation Requirements.—Since apparatus belonging to the household-utensil classification is usually operated on 115- or 230-volt circuits, the insulation requirements do not appear to be hard to meet. Mica and porcelain are both very high in dielectric strength, fortunately, and therefore should be more than adequate for any house circuit. Insulation resistance is high also; and as for dielectric losses, if there were any, we could put them to use, since we are aiming at production of heat. Is there any "headache" in the insulation for appliances?

Shock Hazard.—Shock hazard is the problem of major concern. Heating devices are used by persons in the home in locations where grounded plumbing, wet surfaces, or other well-grounded objects are near. If there is sufficient current leakage from the heating element to the case or other handled parts of the device, a serious shock hazard exists. There is an enormous difference in the vulnerability of people to electric shock, some being able without harm to make rather firm contact with a 230-volt circuit. On the other hand, a few people have been killed by 100 volts. Body resistance apparently is a variable, and the current necessary to paralyze the heart muscles of some persons is quite low. Through many careful studies, attempts have been made to establish safe limits for current through the body, to avoid danger. Since we cannot count too much on the resistance of the body to limit the possible current, we must obtain adequate insulation resistance in the apparatus. A rough rule that seems to

hold is as follows: Most people can feel 1 milliamp. through the body, especially at the elbow (which is considered a sensitive surface). Two milliamperes will produce a distinct shock, and 20 milliamp. is sometimes fatal.

At 115 volts, 1 milliamp. means an insulation resistance of 115,000 ohms, a figure that seems easy to meet until we examine the conditions of service. Devices such as ranges are used under hot and humid conditions. Insulation resistance, we know, decreases rapidly with higher temperature and at heating-element temperatures may be a fraction of the cold resistance. The materials used are necessarily made without means of preventing moisture absorption, so that highly humid ambient conditions may cause low resistance. It is therefore not an easy matter to obtain high insulation resistance under these adverse conditions.

A meeting of the minds of customers and manufacturers on this subject is not to be expected. A value of resistance that would satisfy all customers may be beyond reasonable manufacturing possibilities. For example, the Electrical Testing Laboratories has set up the requirement of 600,000 ohms (0.2 milliamp. at 120 volts) after the apparatus has been kept at 85°F. and 85 per cent humidity for 16 hr. and then put on the circuit and allowed to come to operating temperature. This is considered a stiff test to meet. A countersuggestion is that of the National Electrical Manufacturers Association, calling for 120,000 ohms under the same test conditions. Possibly a sufficiently safe limit lies between the two.

There has been considerable objection made by reputable manufacturers and customer organizations to the cheap heating appliances on the market. At one time there was a large volume of merchandise offered that was not safe from an insulation and shock-hazard viewpoint. Through a process of education and enforcing of local safety-code rules, sponsored largely by the Underwriters' Laboratories, much of this type of goods has been eliminated.

A description of the familiar home appliances will bring out the design of several methods of construction in use. It should be borne in mind that one form of structure may be as safe and serviceable as another, notwithstanding advertising claims. The choice of design is often determined by factors of indirect interest to the user, such as patent situations and manufacturing costs.

Heaters for Electric Ranges. OPEN TYPE.—The open type is made by threading a coiled wire heater into the spiral grooves of a porcelain block, or "brick." At one time, practically all heaters were of this type; and although several newer forms have been developed, the open heater is still extensively used. The ceramic disk, or brick, is made of a heat-resisting unglazed porcelain, with low expansion characteristics. One important requirement is the resistance to thermal shock, since liquids are liable to be spilled during cooking. A cycle of full temperature followed

FIG. 199.—Open-type range heating unit. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

by immersion in cold water is a common test. Since the disk is about 1 in. thick in some sections and the thermal conduction is not high, the ability to stand temperature changes is helped by designing slots, or relief points as in Fig. 199. The limited expansion can take place at these points without piling up excessive stresses. Some way must be devised to hold the heater coil in place, especially when it lengthens on heating. Some ceramic disks are made with bridges across the grooves under which the element must be threaded. Others have knobs or projections that alternate in position on the sides of the grooves (Fig. 199). The coil can be slipped under these points but will be held in place when completely assembled. An important part of any heating unit is the method of terminating the wire for connection to the circuit. In the open-type range brick, a separate porcelain block of the same material is fastened by bolts or a metal clamp to the brick, and the wires of the coils are connected to terminal studs. There may be several circuits to be brought out,

since most heaters have at least low-, medium-, and high-heat positions and some have one or two additional positions.

CEMENTED TYPE.—A second construction is known in the factory by the inelegant term of "mud" heater. A metal disk is cast with spiral grooves in the undersurface. In this groove, a ceramic cement such as alundum is laid, and the coiled heater wire embedded in the cement while its consistency is that of mud (hence the name). The grooves are completely filled with cement. When this is hardened and dried, the wire is permanently held and insulated from the casting (Fig. 200). As might be expected, the method of supplying heat to a cooking utensil is different with this "closed" heater than with the open coil form. The open coil radiates heat to the vessel and provides relatively little surface for conduction of heat. The brick might be considered a secondary radiant source, but not a particularly effective one. The closed metal disk is heated mostly by conduction from the embedded element and transmits its heat both by conduction and by radiation to the cooking utensil. Radiation is less effective, for the temperature of the casting is less than that of the open heating coil. The embedded unit is an efficient heat source for cooking, although its speed in coming to maximum temperature may not be so high as that of other forms. Emphasis (arising from customer demand) is now given to speed in cooking, as well as efficiency of heat transfer. A faster unit is the cemented type enclosed in a thin stainless-steel sheath (Fig. 201), formed under high pressure to give high density in the cement. The terminals of the cemented unit are usually porcelain blocks fastened to the casting.

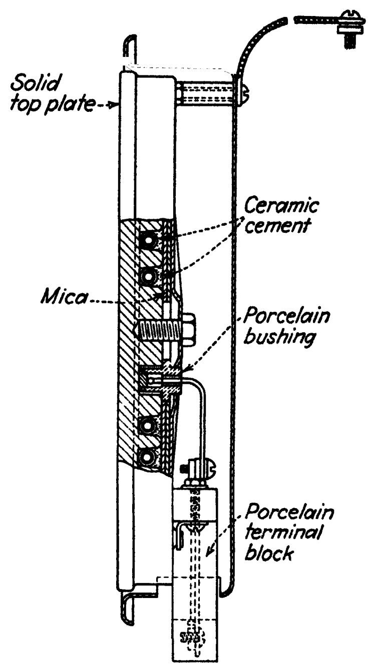


FIG. 200.—Cast cemented range heater unit. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Converted Magnesium.—A third form of heater known by the trade name Corox uses the Backer process of insulating with a metal, strange as it may seem (Fig. 202). In the final form, the

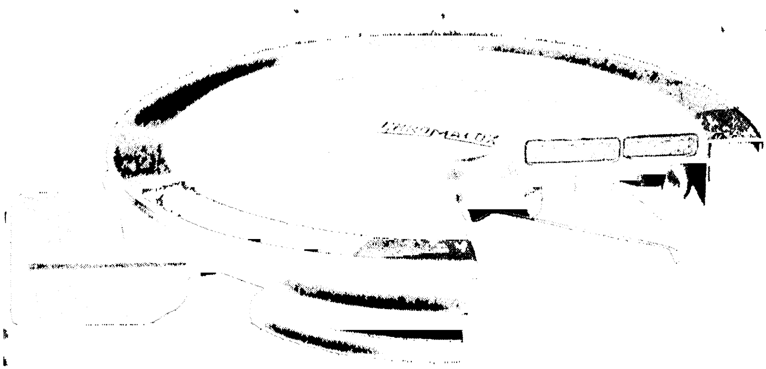


Fig 201.—Metal-sheath cemented range heater unit. (*Courtesy of E. L. Wiegand Co*)

heater coil is surrounded with magnesium oxide, an excellent insulation for high temperature; but the process starts with metallic magnesium. First, the heater wire is coiled and slipped

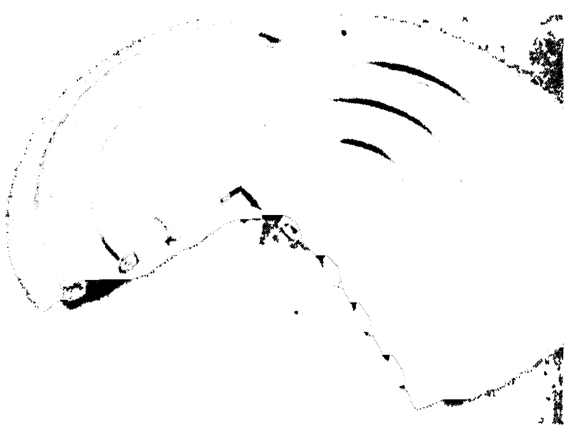


Fig. 202.—Converted magnesium (Corox) range heater unit. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

over a core of magnesium wire. Then a ribbon about ¼ in. wide of magnesium is wound spirally over the heater coil. At this stage the element resembles small armored cable. The heater is laid in a grooved disk stamped from stainless steel and is tacked

in place with ceramic cement and a similar stamped plate placed on top. The two halves are spot-welded at numerous points between grooves. The sandwich then undergoes a chemical transformation. It is treated under high-pressure steam in an autoclave until first the magnesium changes to magnesium hydroxide and then the water is driven off, leaving magnesium oxide. A thorough final heating drives off all moisture, a condition determined by measurements of the hot insulation resistance.

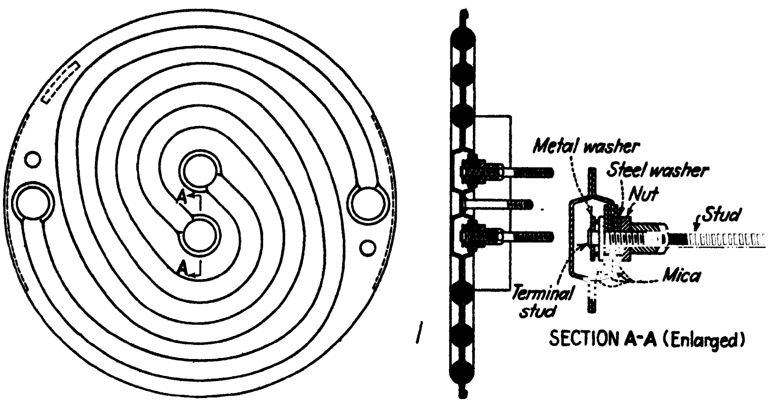


FIG. 203.—Converted magnesium range unit showing terminal construction. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Terminal studs are fastened to and insulated from the lower metal disk. The ends of the heater coils are attached, before steam treatment, to the studs which are threaded through mica washers or a ceramic bushing, insulating the holes through the metal (Fig. 203).

Thermally this heater is similar to the cemented construction in method of energy transfer, except that the mass of metal to be heated is smaller than the cast plate and the heater may therefore be faster. The problem is to obtain sufficient density in the magnesium oxide to give good heat transfer. Too great porosity would be detrimental in two ways. First, it would impair the speed of heat transfer from wire to case. A second fault would be a necessary high thermal gradient through the magnesium oxide, a high wire temperature, and therefore a shorter life of the heater wire.

TUBE HEATER.—A unit combining several advantages is the form that looks like a metal tube of about ¼ in. diameter, bent

into spiral convolutions; or if several circuits are desired, separate spirals are nested concentrically. The tube is easy to keep clean and has small mass, increased speed of heating being the result.

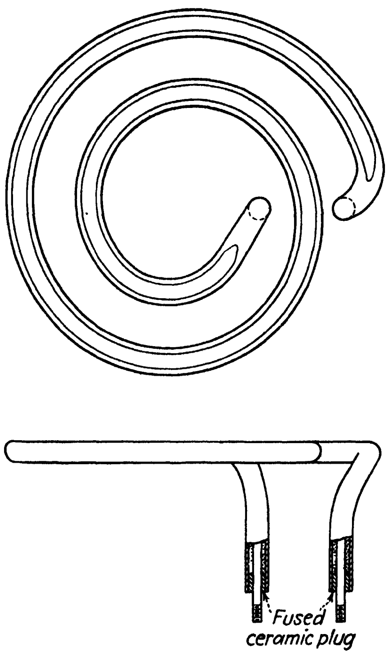


FIG. 204.—Tubular range heater unit. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

A coiled heater is held in the center of a stainless-steel tube of required length, and the spaces are filled with an insulating powder. The insulation is called "periclase," a fused magnesium oxide obtained from magnesite, and is used in the form of a coarse powder about the consistency of sand. It is important, as we have noted, to obtain high density; and this is accomplished by a grading of particle size on the principle used in the selection of concrete aggregate to obtain minimum voids. The filling of the tube is done while the tube is rotated and vibrated. The next operation, after compressing the insulation, is annealing the tube, followed by bending to the spiral shape and turning up the ends for terminals, and finally a flattening of the top of the convolutions to present more contact surface for cooking vessels (Fig. 204).

For terminals, studs are attached to the heater coils before the coils are threaded through the tubes. The studs are centered and sealed in place by ceramic plugs. A terminal block molded of asphalt, asbestos fiber, and cement (cold-molded composition) is assembled between clamps on the lower side of the heater casing (Fig. 205). The studs, threaded on the ends, go through holes in this block and are connected to the circuit wires with washers and nuts.

Flatirons.—The desired direction of heat transfer in irons is the opposite from that in ranges. We should like to force all the heat downward (a difficult objective) and avoid radiation upward,

which is not useful and is uncomfortable to the user. The factor of mass, objectionable in range elements, is a requisite in irons. First, ironing is a combination of heat and pressure; second, a

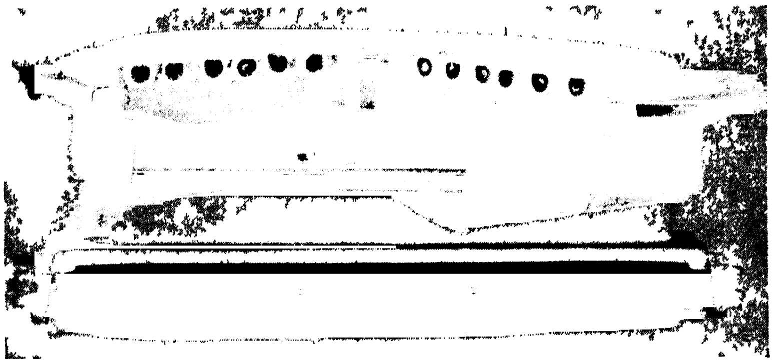


FIG 205 —Cutaway view of tubular range unit and terminal block (*Courtesy of Westinghouse Electric & Manufacturing Co*)

reasonable mass aids in maintaining a uniform temperature. The trend in this device is also toward speed of heating, recovery of heat when very damp clothes are ironed, and also toward lighter weight. Whereas a 6-lb. iron was once considered light,

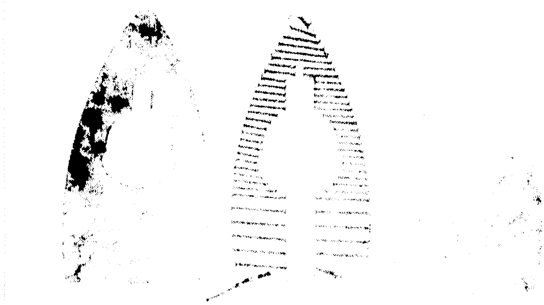


FIG 206 —Mica-sandwich flatiron element (*Courtesy of Westinghouse Electric & Manufacturing Co*)

4-lb. irons are now preferred. All these factors have caused the increase in energy input, so that 1,000-watt irons are common. The problem of insulation has certainly not been made easier by these developments.

TYPES OF ELEMENT.—Three types of heater-element construction will be described: the mica sandwich, the cemented element, and the embedded tube. In each case, the objective is to get the maximum heat into the base of the iron, called the "soleplate."

In one form of *mica sandwich*, a piece of heater mica (selected amber mica) is punched to receive the resistance ribbon, which is

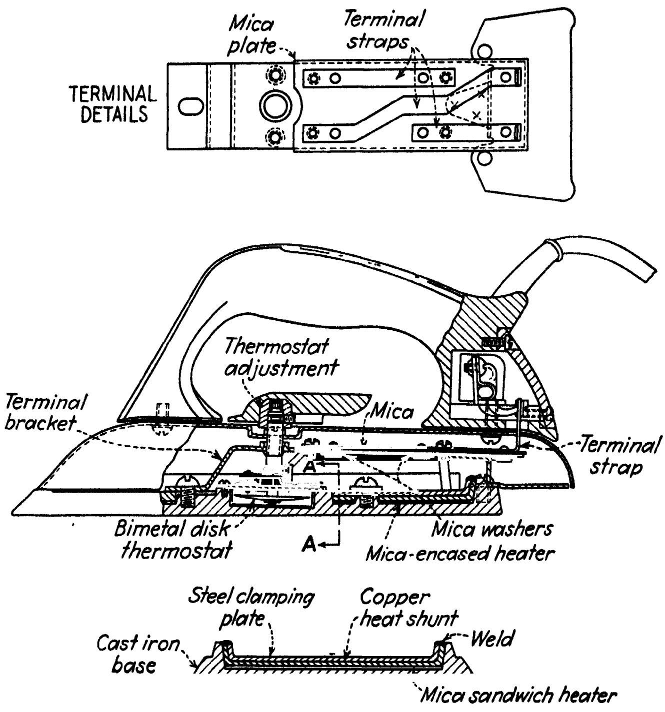


FIG. 207.—Flatiron with mica-sandwich heater, heat shunt, and thermostat. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

wound around the edge and through the openings in the mica card (Fig. 206). Another form of heater unit is made by so slotting a wide ribbon from alternate edges that the equivalent of a long, narrow ribbon is obtained in a small space. On both sides of the element a blank sheet of mica is placed, forming a sandwich. As mechanical protection for the mica, the sandwich may be wrapped in a thin sheet-steel sheath of the same outline. This assembled element is then clamped to the soleplate by bolts

extending from a top cast-iron plate through the heater into the soleplate. Part of the heat generated passes to the upper clamping plate. If good thermal contact between the clamp and soleplate is obtained, some of the heat going upward will be conducted to the soleplate. A special means of accomplishing this conduction is a "heat shunt," built into some designs. A copper sheet is pressed over the heater sandwich and held in contact with the

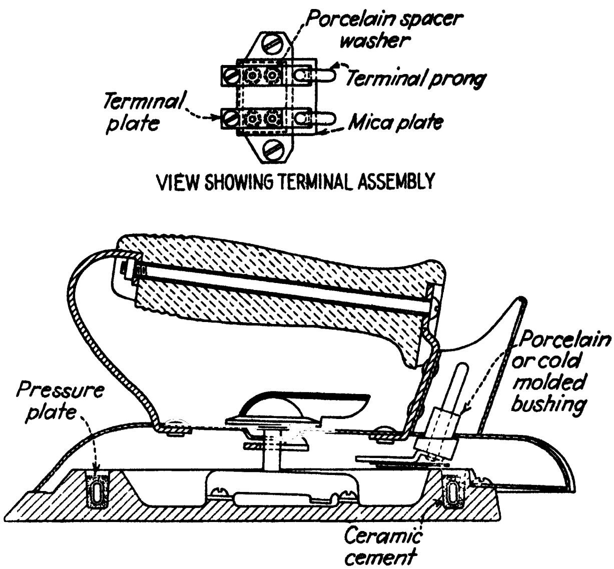


Fig. 208.—Cemented heater flatiron. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

base by a top steel sheet welded in place. Heat is thereby conducted readily into the soleplate from the top surface of the heater (Fig. 207).

The *cemented iron* is constructed in a manner similar to the cemented-, or "mud-," range unit. The soleplate is designed with a groove following the contour of the iron and spaced in from the edge about ½ in. Into this recess the coiled element, which has been previously flattened to elliptical cross section, is cemented with alundum or another ceramic cement. The cement may be held in place by a metal strip forced into the groove above the cement (Fig. 208). Embedding the element in the part to be heated gives a thermal advantage to this type of iron.

The *embedded tube* is a further development of the plan of putting the heat where it is useful. A tube element is used, similar to that used for ranges, and made by encasing the heater coil in a steel tube filled with periclase powder, followed by a compacting process. The tube is cast into the iron soleplate. Sufficient margin in the relative melting points of iron base and the tube alloy must be allowed so that the tube will not dissolve into the base. The ends of the tube project out of the casting so that connection can be made. Another means of fabrication is to braze the tube heater into a groove in the base, a scheme substantially the same in effectiveness. Choice of method is a manufacturing problem.

TERMINALS.—Bringing the connections out to the plug or cord is a separate insulating structure in flatirons, more or less independent of the type of heater element. Some irons have no detachable plug but are designed with the cord permanently attached to terminal strips inside the cover. These strips are mounted with mica insulation on metal brackets or straps fastened to the soleplate. One reason for attaching the cord without a plug is to ensure good electrical contact. Most plugs become looser with use, and the poorer contact causes unwanted heating of the plug, progressively deteriorating the contacts and plug, especially with irons of high rating (1,000 watts). When plugs are used, the element is connected to terminal pins. There are two ways of holding the pins, one by mica washers and bushings in a metal bracket, and the second by ceramic blocks held in a metal bracket and through which terminal pins are bolted. In the attachment plug, the spring prongs that engage the terminal pins will keep in good contact longer if made of silver monel. The attachment-plug molding may be formed of heat-resisting phenolic compound. Even the best has a limited life, ultimately failing by disintegration of the bond. Plugs made from cold-molded material (asbestos, Portland cement, and other ingredients) will last longer but have poor surface appearance, usually not acceptable with a highly finished flatiron.

THERMOSTATS.—A snap-acting thermostat is generally considered an integral part of a flatiron and often of other heating appliances. The actuating element may be a bimetal strip with a toggle-spring action or a dished bimetal disk that snaps from a concave to a convex shape, the latter being the well-known

Spencer thermostat. The contacts, both the stationary and those which may be mounted on the bimetal element, are usually insulated from the metal by mica strips, washers, or collars (Fig. 209).

Toasters.—Many toaster elements are made with coiled-wire heaters which can be supported in various ways. An early type of toaster had a flat ceramic core provided with grooves and holes

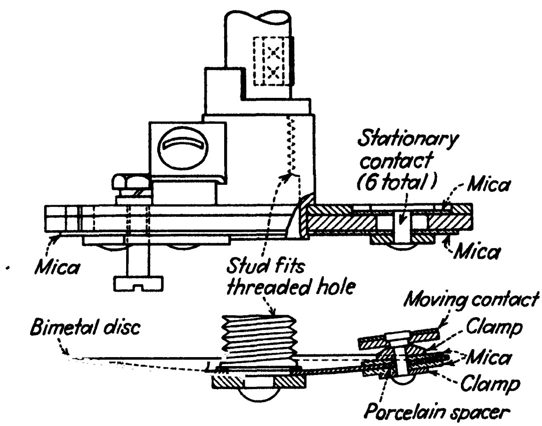


FIG. 209.—Snap-acting flatiron thermostat. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

through which the coiled wire was threaded. Another construction consists of mica strips at the top and bottom of the toaster, held in the metal frame. The heater wire is looped over or through the mica. Still another method is to string the coil through ceramic bushings or spools clamped in the toaster frame. Where ribbon resistance material is used, a mica card, usually made of mica splittings without bond, is the core. Slots and holes secure the ribbon just as in the sandwich type of flatiron element (Fig. 210).

Terminals are very simple. The plug pins are insulated from the frame or base of the toaster by mica washers. Commonly, a recessed shoulder is stamped around the holes in the frame to center the washers, and then the pin or stud is put through the washer and held by nuts over both sides of the mica washers.

Waffle Baker and Sandwich Grill.—These devices usually have a heater in both top and bottom halves. Connecting the two and shunting the hinge is a flexible spiral metal guard containing

the asbestos-insulated conductors. The two heating units may be constructed in a form called a "skeleton heater" (Fig. 211). This consists of a formed sheet-metal frame with holes at appro-

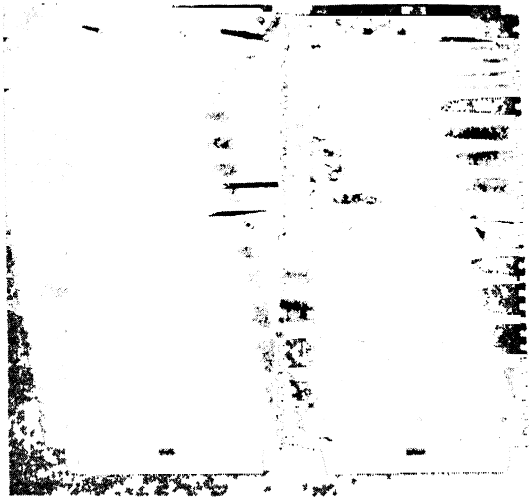


FIG 210 —Mica-card and ribbon heater for toaster (*Courtesy of Westinghouse Electric & Manufacturing Co*)

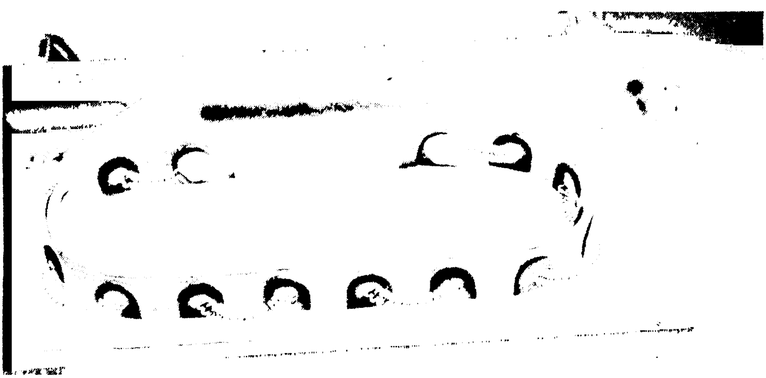


FIG 211 —Skeleton heater for sandwich grill (*Courtesy of Westinghouse Electric & Manufacturing Co*)

priate intervals. Ceramic spool-shaped bushings are fastened in these holes or slots, and the heater coils stretched between the bushings. This is a simple and rugged construction, not subject

to deterioration and not impeding the radiation of heat to the cooking surface. The same general construction is used in larger dimensions for heaters in range ovens or broilers (Fig. 212) and

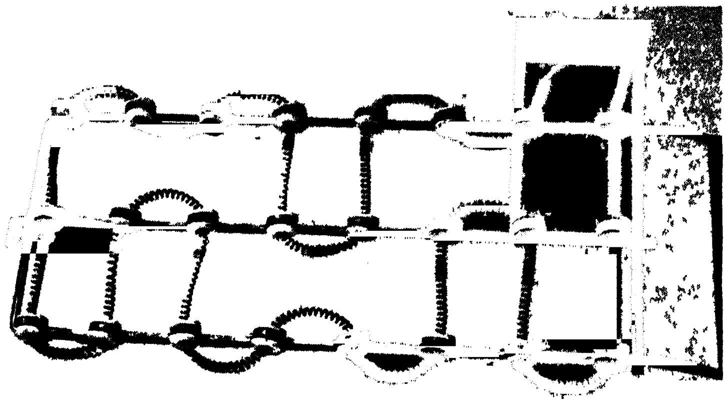


FIG 212—Skeleton heater for range oven (*Courtesy of Westinghouse Electric & Manufacturing Co*)

also in table stoves. The other types of heaters used for flatirons, such as the mica sandwich, cemented element, or cast-in element, might also be used for waffle bakers or sandwich grills.

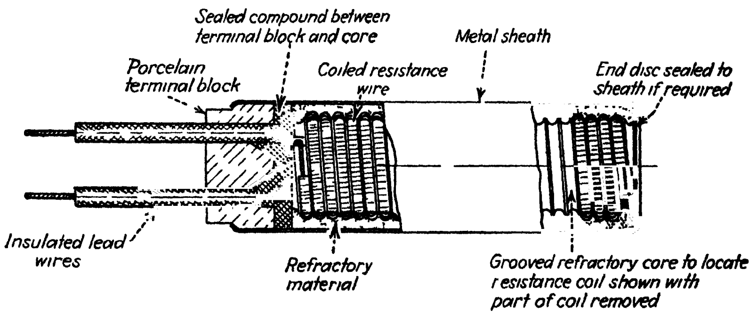


FIG 213.—Cartridge heater unit with ceramic insulation (*Courtesy of E. L. Wiegand Co*)

Roaster.—The bottom is heated by a conventional type of element, and in addition the sides must be heated. For this purpose a wrapped heater is constructed on the sandwich principle, except that asbestos sheet instead of mica is used. This band heater is cemented in place around the inner shell of the

roaster and further held by the thermal insulation (mineral wool) filling the space between the outer shell and the inner shell.

Ironer.—The heater for an ironing-machine shoe must be thin and flexible enough to be clamped against the curved surface. A slotted wide ribbon element is placed between thin mica plates with the terminals of the strips threaded through slots in the mica. The element is shaped like a hollow rectangle. Stitching together the mica sheets on a sewing machine holds the heater in place until the clamping plate is applied.

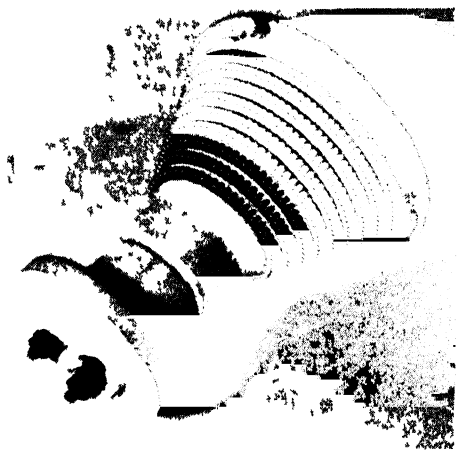


FIG 214—Reflector heater unit with refractory porcelain core (*Courtesy of Westinghouse Electric & Manufacturing Co*)

Space, or Strap, Heaters.—The same type of unit is built into space, or strap, heaters by wrapping the mica strip in a metal sheath, openings being left for the ends of the heater ribbon to emerge from the mica. Cemented units are also made for strap heaters. In these, a layer of cement is placed in the bottom of the sheath, and the heater ribbon embedded, covered over with cement; after drying, the top sheath is located, and the edges are rolled together under high pressure.

From these descriptions, it will be evident that very few different materials are used. Mica and ceramic materials, the latter in powder, cement, or molded (and fired) forms, suffice for all sorts of applications (Figs. 213, 214).

Furnaces.—At two points in the construction of resistance-type electric furnaces, insulation in the electrical sense is encountered.

The first is the mechanical support for the wire, rod, or strip form of heating element; and the second is the entrance lead by which the electrical connection is made through the thermal insulation of the furnace, to the heater on the inside.

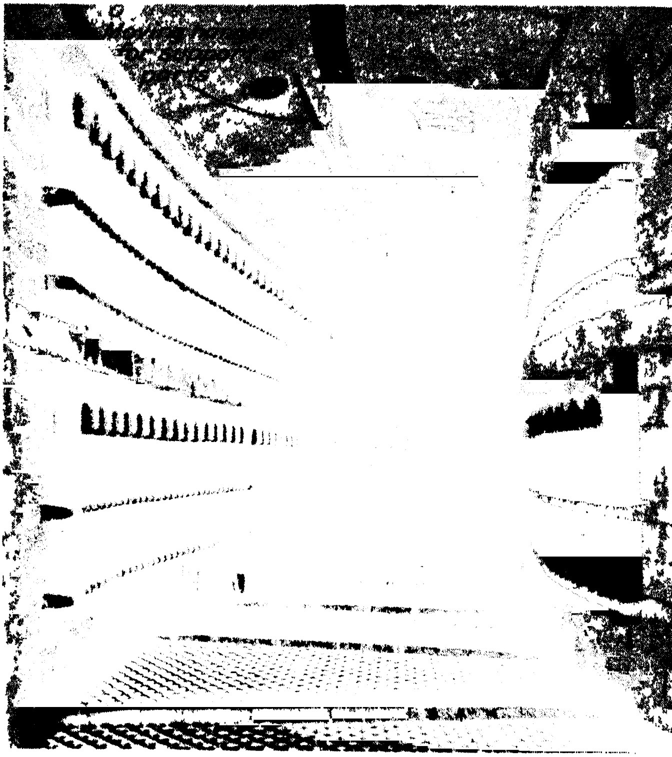


FIG 215—Hanger blocks supporting heater strap in continuous furnace. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

HEATER SUPPORTS.—Refractory bricks used for furnace linings are rather weak mechanically and are consequently not usually suitable for supporting the heater elements. Special refractory materials have been developed for this purpose. In one method of construction, the supports (called "hanger blocks") are set in the furnace wall at desired locations, taking the place, at those points, of a brick of the furnace wall (Fig. 215). Hanger blocks have projections, hooks, or knobs over which the heater element

is strung. Another scheme uses metal (heat-resisting) hooks set in the furnace brick wall to hold the upper loops of the heater (Fig. 216). The lower ends are clamped between the flanges of refractory spools fastened to the furnace wall by heat-resisting metal bolts. More interest centers in the properties other than

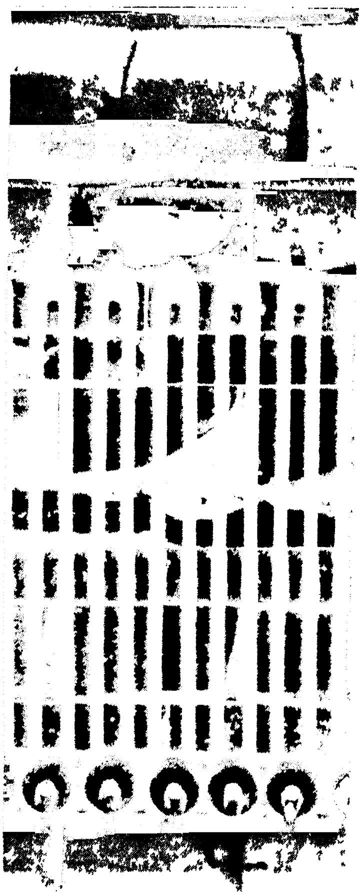


FIG 216.—Hook and spool supports of rod heater element of furnace. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

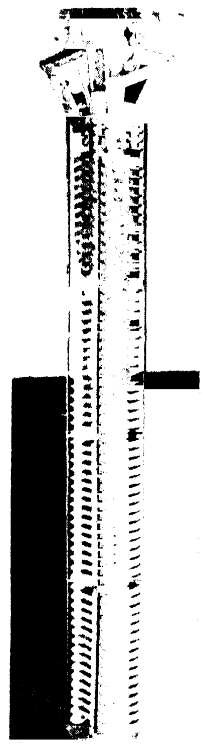


FIG 217—Core heater unit for strip-steel coil annealing furnace. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

electrical. Mechanical strength at high temperatures, resistance to heat shock, ability to withstand the furnace atmosphere chemically, and resistance to disintegration are far more important than the electrical resistance. Most furnace voltages are

relatively low, requiring no exceptional specifications for electrical insulation.

Uniformity in temperature distribution throughout the furnace can be obtained with any known type of charge (work loaded into furnace) by suitable location of heating units. Sometimes the sides only need to be heated, sometimes the bottom, top, or a combination of all locations. The method of support is adapted

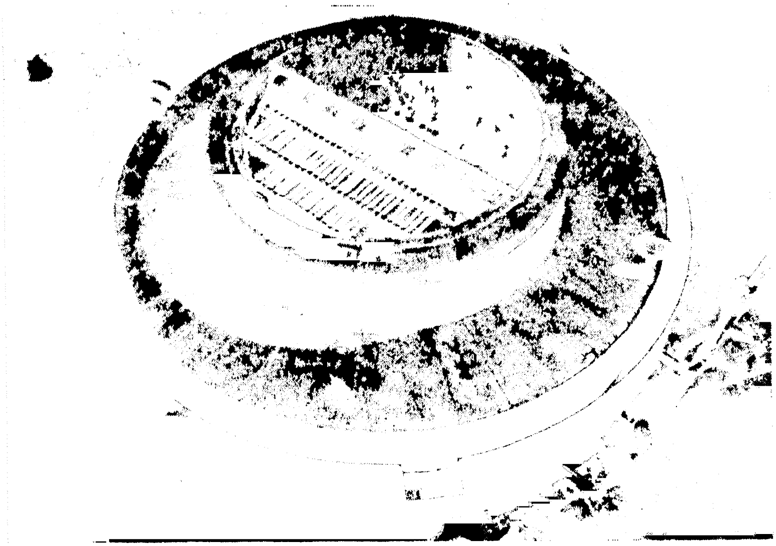


FIG 218 —Base heater for bell-type annealing furnace. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

to the location required, which changes the form of hook or hanger; but the principles and materials are similar. For annealing steel strip in coils, a cylindrical furnace is used, provided with a central core heater as in Fig. 217. Here a metal frame, insulated with ceramic blocks, carries the heater ribbon. A heater for the base of a bell-type annealing furnace is shown in Fig. 218.

TERMINALS.—Bringing out the connecting terminals from a heater in an air-atmosphere furnace is quite simple. The conductor (usually of the same material as the heater but larger in cross section) can be inserted through a hole in the brick wall or through a refractory tube cemented into the furnace lining. If the furnace has an outer metal shell, a porcelain bushing or asbestos terminal block is sufficient at this cooler location.

More and more heating processes now require controlled atmospheres above and below the ambient pressure of the room. Furnaces for operations of this sort must be relatively or completely gastight. For example, air leaking into a hydrogen furnace would be disastrous, and hydrogen leaking out would be expensive. Batch furnaces in which the charge is loaded periodically may be sealed with sand, water, molten metal, or oil. Continuous furnaces require a gas lock or other device for at

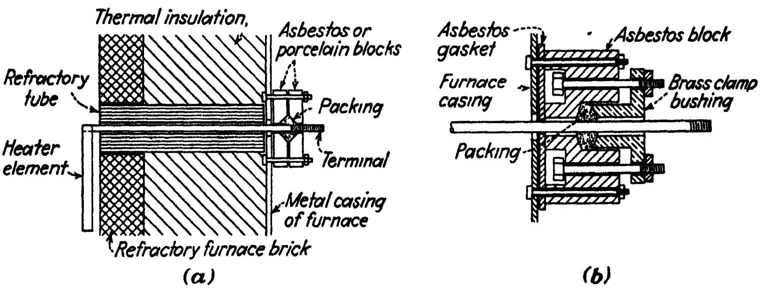


FIG. 219.—Insulation of terminals of electric furnace.

least reducing the leakage of gas in or out. Likewise, the electrical connections must be gastight.

Of the many designs available for accomplishing the desired end, two are shown in Fig. 219. In one of these (Fig. 219*a*), the terminal rod is brought through the lining and thermal insulation in a refractory tube, then through a large clearance hole in the furnace casing and into a packing gland. Two porcelain or asbestos blocks, bolted to the shell and containing a diamond-section mass of asbestos packing, effectively seal the terminal. The packing material may have a cementing bond added. Tightening the holding bolts wedges the packing around the conductor. A similar result is attained by the construction of Fig. 219*b*, which more closely resembles a packing gland for steam-valve stems and pistons. Here a metal collar with sloping inner face compresses packing against an asbestos block and the conductor. The compression collar is thus in contact with the lead and must be insulated from the furnace shell.

CHAPTER XV

LAMPS AND TUBES

An electric lamp is a device in which useful radiation at visible light frequencies is produced by electrical means. The radiation may not be wholly in the visible spectrum but may include infrared for paint drying or ultraviolet for biological purposes. Two classes of lamps are recognized: filament and vapor types. The filament lamp is one in which light (or heat) is produced by a metallic filament through which current flows to heat it to the required temperature. Such a lamp is built in a glass bulb containing either a vacuum or an insulating gas. Vapor lamps may have filaments, also, but not as major sources of light. Such filaments are the means of starting an electric discharge through a gas or vapor contained in the lamp. In this case the gas is used as a conductor, instead of an insulator. The functional insulating parts in a lamp are then the *glass stem* and *press* through which current is brought into the bulb, the *glass bulb*, and the *gas space*, which is an insulator in filament lamps and a conductor in vapor lamps (Fig. 220).

Filament Lamps.—At the *press*, the lamp leads are close together, sealed into the glass. Any current leakage at this point, then, should be avoided. Glass, as has been noted before, is a supercooled liquid that behaves like an electrolyte, particularly at high temperatures. If temperatures are high enough, sufficient current flows in the press to electroplate metallic lead out of the lead glass onto the wires. After sufficient time the porous lead coating increases in thickness enough to destroy the seal between wires and glass and may even burst the press. On direct current, the plating deposits on one wire only and reaches the dangerous point much faster than on alternating current. As might be expected, 230-volt lamps are more subject to this trouble than 115-volt lamps.

There are two ways of curing this trouble. The more obvious one is to keep the temperature of the press low, which can be done

by design proportions or by a baffle. In many large lamps a mica disk is usually mounted on the wires inside the bulb to deflect heat from the filament. What about the possibilities of decreas-

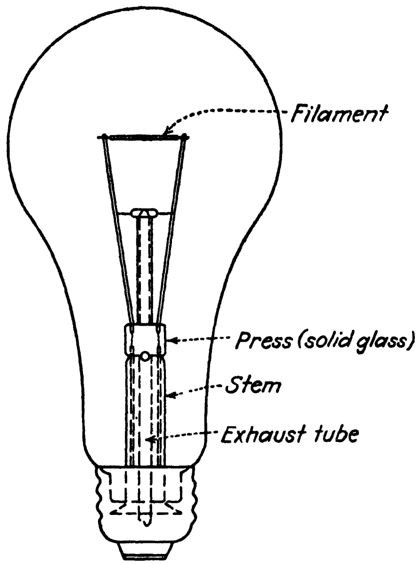


Fig. 220.—Standard filament lamp. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

ing the electrolytic current in the press by using a different glass? Contrary to what might seem reasonable, if a glass of higher lead content is used, the resistance is increased and the leakage current

Table XXI

Part	Type of lamp	Glass	Resistivity ohm-cm. at 350°C.
Stem and press......	Gas filled	High per cent lead	95.5
Stem and press......	Vacuum	Low per cent lead	13.3
Bulb...............	Majority	Lime	0.17

decreased. The heat problem is worse in gas-filled lamps (gas has higher heat conductivity than vacuum), and so the practice is to use a higher resistance glass (higher lead content) for presses in gas-filled lamps than in vacuum lamps. Lime glass is much lower in resistivity than lead glass and is therefore unsuitable for the press.

From a fabricating point of view, lime glass is preferable because it is tough, has low density, or more pieces per pound, and is lower in cost than lead glass. Lime glass is therefore practically always used for the bulb.

Lamp glasses can be summarized as shown in Table XXI.

Vacuum or Gas Filled.—At one time all lamps had a vacuum dielectric surrounding the filament. Now more gas-filled lamps for standard lighting circuits are made than vacuum lamps. This change came about in the search for greater light efficiency, but gas in itself is not the cause of the improved efficiency. To understand the problem, we must stop to examine what goes on in a lamp throughout its life. Tungsten from the filament is continuously being evaporated at the surface during operation of the lamp and deposits gradually at the cooler portions of the bulb. The familiar blackening increases, and the filament grows thinner, faster in some spots than others; finally it burns apart or breaks at one of these spots, unless the lamp is thrown away before that happens. Evaporation of the filament is then the serious problem affecting lamp output and life. Efficiency of illumination can, of course, be stepped up by operating the filament at a higher temperature, but this increases the evaporation rate. Inert gas in a lamp bulb, then, is used to suppress evaporation and make it possible to operate the filament at a higher temperature, while the desired life of the lamp is still maintained. The pressure of the gas is effective in preventing metal vapor from being given off by the filament. Most of the best gases for this purpose are high in atomic weight. Any gas in a bulb will conduct heat away from the filament, an undesired effect; and the better the heat conductivity of the gas, the more energy is lost to the glass walls through gas conduction. There is a balance point in size of lamp bulb at which the gain in light efficiency possible by raising the filament temperature and by suppressing the evaporation by a gas atmosphere is offset by the loss of energy through the gas to the glass. For this reason, lamps smaller than 30 watts for 115-volt service are still made with a vacuum dielectric. Miniature lamps for low voltage are sometimes the vacuum type, also.

The energy wasted in a lamp is made up of

1. Watts radiated below the visible spectrum.
2. Watts conducted to the base through the support.

3. Watts conducted through the gas.

The third item is negligible in vacuum lamps.

GAS.—Which inert gas is the best to use in filament lamps? The specifications one might prepare would call for a gas that has high molecular weight, low heat conductivity, high ionization potential, and low cost.

TABLE XXII.—POSSIBLE GASES FOR LAMPS
(Arranged in order of decreasing thermal conductivity)

Gas	Density (air = 1)	Atomic weight	Thermal conductivity	Ionization potential, volts velocity
Hydrogen	0.0695	1.008	0.000380	13.5
Helium	0.276	4.00	0.000338	24.6
Neon	1.4	20.20	0.000190	21.5
Nitrogen	0.9713	14.01	0.0000566	16.7
Argon	2.75	39.88	0.000038	15.4
Krypton	5.71	82.92	0.000021	13 3
Xenon	8.99	130.2	0.000012	12.1

Immediately we might choose xenon as the best for the purpose, except for one thing—cost. The three best gases are extracted from air by a freezing-out process, and the rarity makes them expensive, especially krypton and xenon. For general-purpose lamps, these two are therefore out of the question, for the present.

TABLE XXIII

Gas	Source
Hydrogen	Electrolysis of water
Helium	From certain natural gas
Neon	From air (1 part in 60,000)
Nitrogen	From air (80 % by volume)
Argon	From air (1 part in 100)
Krypton	From air (1 part in 1 million)
Xenon	From air (1 part in 11 million)

Xenon and *krypton* are obtained together (they are difficult to separate) and are used only where the utmost in light efficiency can be justified, as in portable miners' lamps for use at 6 to 10 volts. In this application the power source must be carried

around, and the maximum light must be obtained for the energy expended. Another reason, besides the cost, why these two gases cannot be used in the pure state for standard 115-volt lamps is that the ionization voltage is too low. Arcing at the lead-in wires would occur. Ionization potential is the potential (usually expressed in volts) through which an electron must fall freely to attain a velocity sufficient to dislodge another electron upon collision with an atom.

The next possibility is argon, which is the chief constituent of common lamps. At 115 or 230 volts, the ionization potential of pure argon is too low, and so a mixture of nitrogen and argon is used. The range is 50 per cent argon to 99.6 per cent argon, the latter figure occurring in low-voltage automobile lamps. House lamps (115 volts) commonly contain up to 98 per cent argon. Projection lamps are a special problem, for filament temperatures are high and the leads are closely spaced inside the bulb; for this type, pure nitrogen is used.

The pressure of gas desired at operating temperature is about 1 atmosphere, for any higher pressure would scatter the glass if the bulb should break. To obtain this value, the pressure in a lamp at room temperature is about 600 mm. of mercury.

Vacuum lamps are usually pumped to a pressure of 30 microns or lower. The "getter" placed inside the lamp cleans up the remaining gas, so that as used the pressure in a lamp is too low to measure.

Outside of the bulb of a lamp, the socket parts require separation by an insulator, commonly a black glass into which the ferrule and center contact are molded. These are held to the glass bulb by a cement that has no insulating function.

Some lamps have a fuse in the base that is protected by an asbestos sleeve to prevent the arc from short-circuiting the socket. In certain series lamps the hollow stem contains magnesium carbonate surrounding the wires. This is to snuff out any arc that starts as a failure at the press and proceeds outside the bulb into the stem.

Vapor Lamps.—In vapor lamps, gases instead of being insulators are chosen expressly for conducting characteristics. The natural choice is metallic vapors, of which sodium vapor and mercury vapor are the most important. Both these metallic

vapors, when conducting current, give out a characteristic light, the sodium a yellow and the mercury a blue-white. Present designs of both sodium and mercury lamps require other gases to make starting easy. Neon and nitrogen blends are used in mercury-vapor lamps designed for high output in the ultraviolet region. Where lower ionization voltage is essential, neon mixed

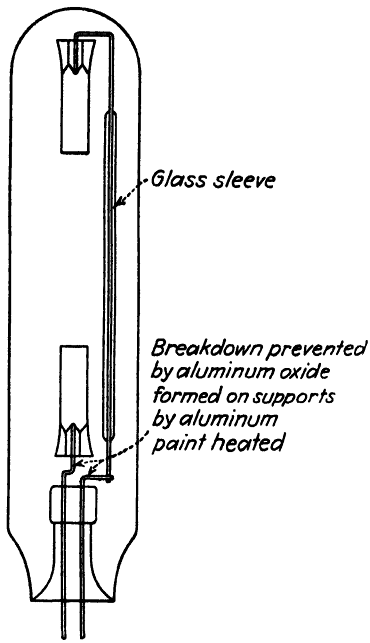


FIG. 221.—Ultraviolet Sterilamp insulation. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

with argon is added to the illuminant vapor. The fluorescent Lumiline lamp is a special form of mercury-vapor lamp in which argon is used to assist in starting. When it is running, the ultraviolet radiation of the mercury vapor at wave length 2537 angstroms strikes a fluorescent coating on the walls of the tube and causes visible light to be emitted. The color of the light depends on the character of the fluorescent material. An irreversible frequency transformation (ultraviolet to visible) takes place. Neon additions are made to sodium-vapor lamps, chiefly for starting the discharge but incidentally as an auxiliary source of illumination.

The same problem of electrolysis appears in vapor lamps as in filament lamps. In some designs the temperature is even higher than in filament lamps. Selection of glass for support beads and in the presses must be carefully studied.

Since gases in vapor lamps are easily conducting, having low ionization potentials (metal vapors have ionization potentials of 5 to 10 volts), there is often a vulnerable point in the construction where breakdown might occur. Spacing of leads must be watched. An example of a special problem of this nature

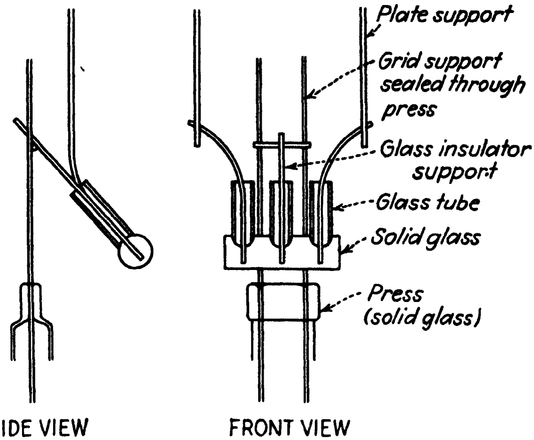


FIG. 222.—Means of obtaining long creepage path between grid and plate supports in industrial electronic tube.

appeared in one form of the ultraviolet source known as the "Sterilamp."[1] As shown in Fig. 221, the discharge electrodes or terminals are at opposite ends of the tube but are supported and connected to the supply at one end. The connecting lead that supports the electrode farthest from the socket is covered with a glass sleeve for insulation to prevent the discharge from terminating at the wire. But at the press the two wires are bare and close together. Arc breakdown at this point is prevented by a coating of aluminum oxide on the wire, obtained by painting with aluminum paint and then heating.

ELECTRONIC TUBES.—Many forms of electronic tubes require extremely high insulation resistance between elements, such as plate and grid. The usual distance through glass presses and

[1] Westinghouse Electric & Manufacturing Company.

over the surface of the glass support beads is insufficient. In these cases, a special construction is used, consisting of glass tubes over wires sealed into glass rods. The surface resistance is thus obtained by lengthening the creepage path. One form is shown in Fig. 222.

MERCURY-VAPOR LAMP.—The mercury-vapor lamp has an inner tube of quartz in the ends of which electrodes of thorium

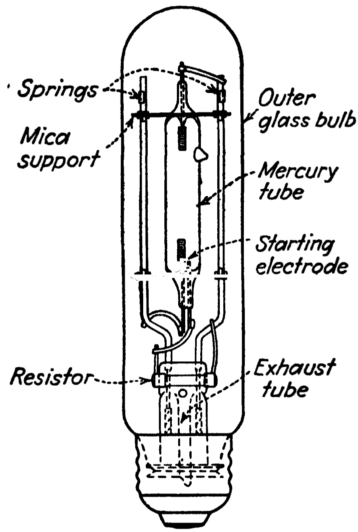


FIG. 223.—Mercury-vapor lamp construction. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

are sealed. Quartz is used because of its resistance to high temperatures. At one end of the quartz tube a starting electrode is sealed near the main electrode. The quartz tube filled with mercury vapor is mounted inside a glass cylindrical bulb, held in place between support posts by mica washers. At the base the resistor for the starting electrode is fastened, so that the lamp is self-contained (Fig. 223). One reason for the outside bulb is the sensitivity of the mercury lamp to temperature changes. It must be kept hot during operation, and the starting time is reduced when thermal insulating space is present.

SODIUM LAMP.—The same is true of the sodium lamp, except that in this case the lamp unit is mounted but not sealed into an outside vacuum bottle. Outside the sodium tube, there is first a

layer of air, then a double-walled tube with vacuum between. Each electrode assembly consists of a filament cathode inside a hollow rectangular anode. Mechanically, the upper-electrode

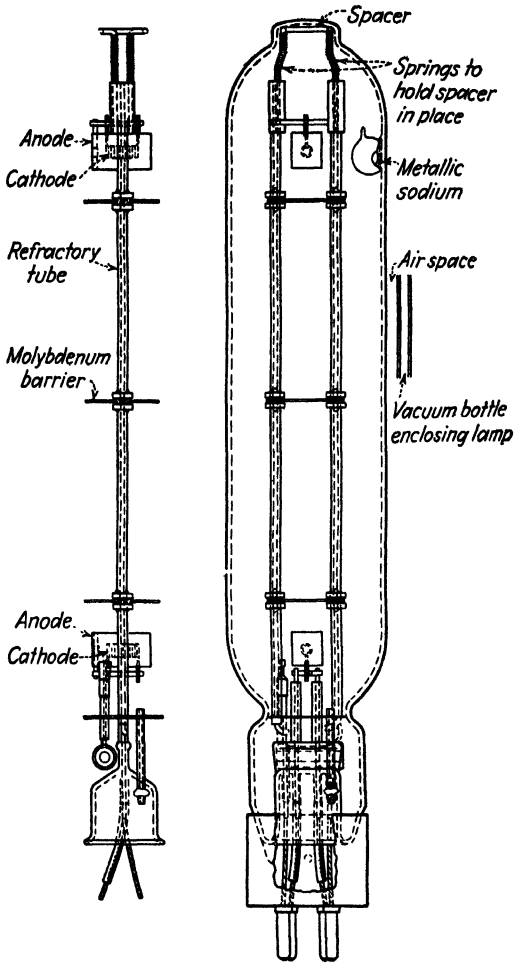


FIG. 224.—Sodium lamp construction. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

parts are carried on rods insulated with ceramic tubing (Alsimag). The starting resistor is mounted near the base, as in the mercury lamp (Fig. 224).

CHAPTER XVI

METERS, INSTRUMENTS, AND RELAYS

Watt-hour Meter.—The watt-hour meter, upon which the electric utility depends for determining its income and in which the customer must place confidence that he will not be overcharged, is more of a mechanical device than it is electrical. To be sure, electrical phenomena actuate it; but the chief design features that ensure long-time accuracy, ruggedness, and low-cost serviceability are largely mechanical parts.

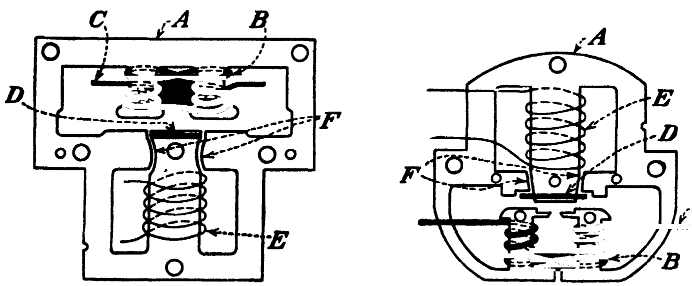


FIG. 225.—Single-phase watt-hour meter elements. *A*, magnetic circuit; *B*, temperature compensating loop; *C*, current coil; *D*, lag loop; *E*, potential coil; *F*, leakage gaps. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The coils, which produce the magnetic fields upon which the action of the meter depends and which constitute the stator of a simple induction motor, are quite simple. The rotor is still simpler, being the familiar aluminum disk whose speed is maintained proportional to power of the metered circuit by the combined driving force of the coils and the retarding force of the permanent magnets. There is no insulation required for this eddy-disk rotor.

The coils in the standard single-phase house meter are three in number: a potential coil of many turns, the current in which lags the potential by 90 deg.; and two current or series coils of only a few turns of wire heavy enough to carry the load current. The

potential coil is placed on one side of (above or below) the rotor disk, and the two current coils are on the opposite side. Typical forms are shown schematically by Fig. 225 and photographically in Fig. 226.

For the potential coil, small enameled wire is used. Layer insulation consists of thin glazed paper (Glassine), and the outer edges of the wound coil are protected from the electromagnet iron by strips of paper or cellulose acetate sheet.

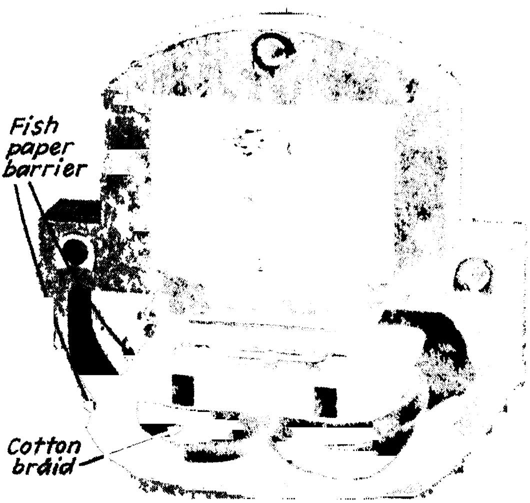
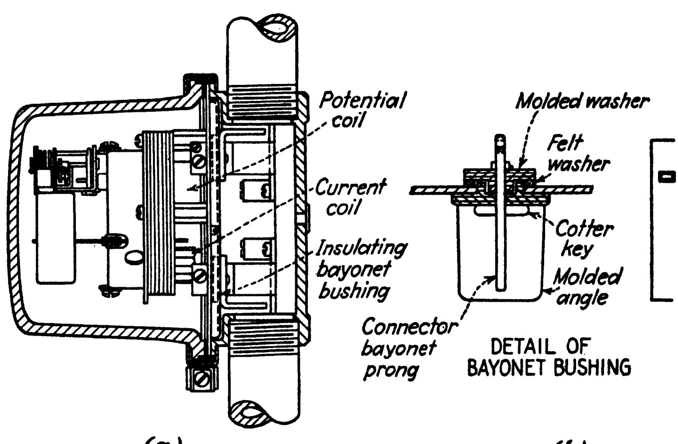


FIG. 226—Single-phase watt-hour meter element (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

The series coils are wound of heavy copper wire or cable, covered with an untreated cotton braid. Over these conductors cotton sleeving is placed from the point where the wire leaves the coil to the terminal. Ground protection is provided by fish-paper barriers around the iron and above and below the coils. The impregnation operation is all accomplished at one time. After the coils are assembled on the iron, the whole assembly is dipped in black varnish (gilsonite type) and then baked.

Getting the circuits in and out of the meter case is an important part of the construction. The usual indoor meter has a simple molded phenolic terminal block with a metal cover over it, and the wires are brought in through holes or bushings on the block (Fig. 227). On new installations, practically all meters are now

FIG. 227.—Watt-hour meter with molded terminal block. (*Courtesy of General Electric Co.*)



(a) (b)

FIG. 228.—Socket-mounted watt-hour meter. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

mounted outdoors. The older arrangement of installation had a fuse block and switch ahead of the meter; and if any insulation failure happened because of lightning or surges, the switch and fuse block "took it." Now the meter is connected directly on the supply lines. A higher insulation level (5,000- to 10,000-volt test) is therefore needed in the insulation provided at the terminals of the meter, which is built into the socket to which outdoor meters are detachably fastened (Fig. 228*a*). The socket

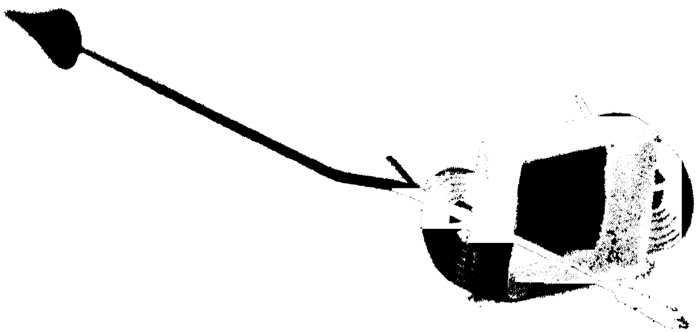


FIG. 229.—Moving coil of D'Arsonval instrument. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

casing is lined with insulating paper, and the terminals are mounted on high-quality phenolic molded blocks which have ample creepage surface formed by ridges. Bayonet lugs on the meter itself project through the meter base, well insulated by molded bushings or a laminated base plate. One form of bushing is that in Fig. 228*b*.

Instruments.—An instrument is a device for indicating instantaneous or present values of electrical quantities, rather than an integrated quantity such as the watt-hour meter records. Sometimes the dividing line is indistinct; in demand indicators, for example, time is a factor of the indication. But, generally speaking, an instrument means an indicating rather than a recording device.

Electrically, instruments are almost without number in the varieties of detailed construction, range, and appearance. They

can, with reference to insulation, be divided into three major classes, as follows:

1. D'Arsonval type.
   Moving element has insulated coils.
   Stationary element, no insulation.
2. Dynamometer type
   Both elements have insulated coils
3. Moving vane type
   Moving element requires no insulation.
   Stationary element has insulated coils.

D'ARSONVAL MOVEMENT.—The coil itself has to be as light as possible. A rectangular aluminum bobbin insulated by an oxide

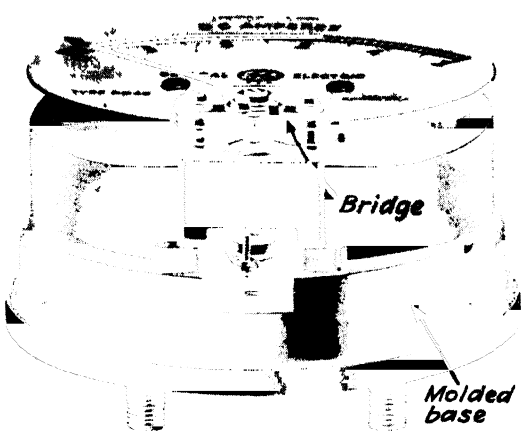


FIG. 230—Assembled D'Arsonval movement (*Courtesy of General Electric Co*)

coating usually forms the support upon which the very fine enameled wire (#36 or finer) is wound (Fig. 229). The two pivots are cemented to the enameled wire coil over a strip of thin insulating paper. Both pivots carry the spiral torque springs through which current is brought to the coil, and one pivot assembly also carries the pointer. The next point to consider is the pivot bearings, which are mounted with the zero-adjustment mechanism on metal "bridges" attached to the meter magnet (Fig. 230). Obviously, one pivot must then be insulated, either at the bearing or at the ends of the bridge. Best practice follows the plan of insulating the support of one bridge (often the

lower) by insulating paper or fiber bushings and washers. In such construction, one coil terminal is connected so that the whole bridge, permanent magnet, and bearing are "live," and the other coil terminal is connected through the spring to the insulated bridge. Where this construction cannot be used, the bearing (jewel mounting) has to be insulated from the bridge by bushings and washers (Fig. 231). Usually the whole movement is then mounted on a molded insulation base. The voltage drop through the moving element, for which the bridge or bearing must be insulated, is seldom more than 5 volts.

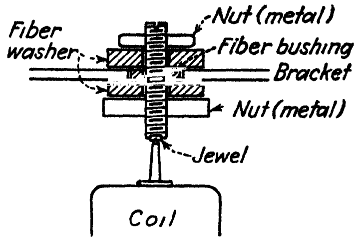


FIG 231 —Insulation of lower pivot of D'Arsonval instrument.

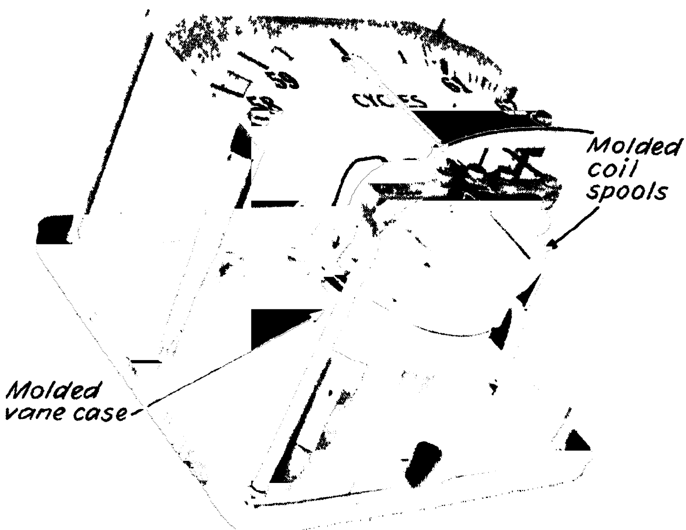


FIG. 232.—Dynamometer instrument (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

DYNAMOMETER MOVEMENT.—The moving-coil construction is similar to the D'Arsonval type. The bobbin in some sizes may be much larger, so that the wire wound on it does not make a very rigid surface on which to mount the pivot parts. Then silk tape,

varnished, is used to cover and bind the moving coils, before mounting the pivots. At the lower end of the movement a damping vane is frequently attached. This moves in a damping chamber which also has an insulating function. It is molded of phenolic or other resin powder and serves as an insulating support

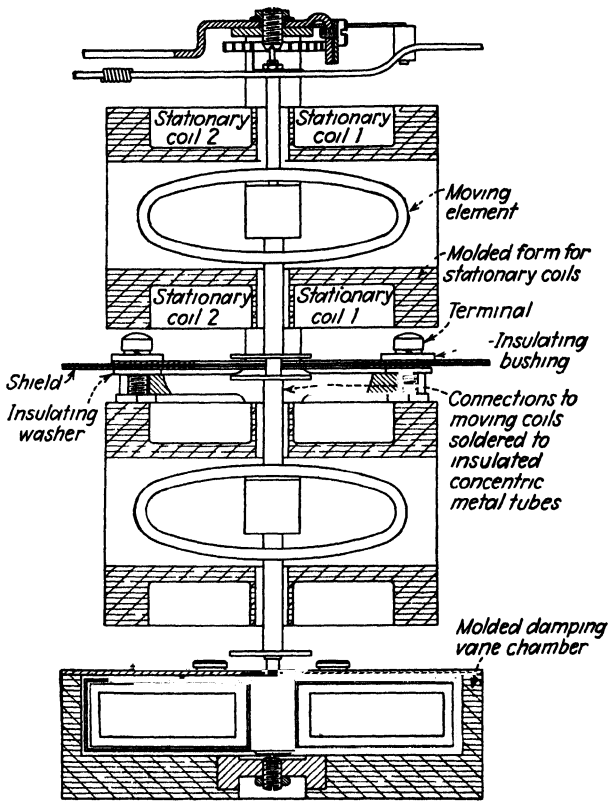


FIG. 233.—Two-element dynamometer instrument. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

upon which the movement is mounted and is thereby insulated from the rest of instrument (Fig. 232). The top bridge is fastened to the molded damping chamber by studs. On a molded spool, sometimes of elliptical shape, the stationary coil is wound, of enameled wire. The stationary-coil assembly fits over the moving coil on the support for the upper bearing and is insulated therefrom by the molded spool (Fig. 233).

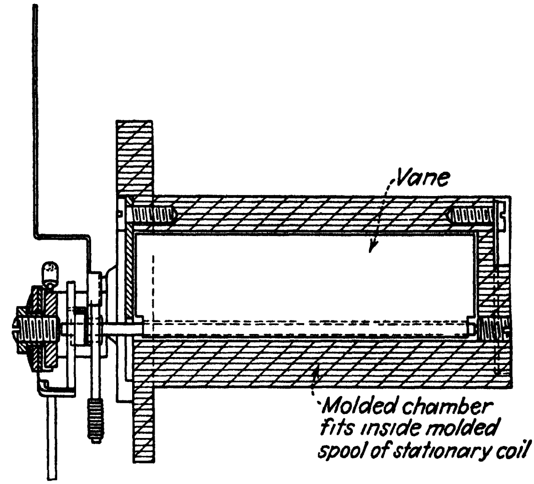


FIG. 234.—Element of moving-vane instrument. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

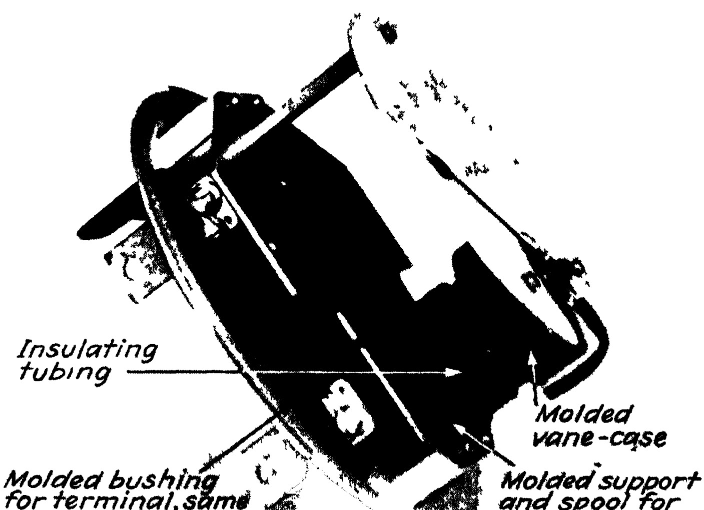


FIG. 235—Mounting of moving-vane element (*Courtesy of Westinghouse Electric & Manufacturing Co*)

MOVING-VANE TYPE.—The moving iron vane is not connected to any circuit and therefore requires no insulation itself. Small instruments of this type often consist of a molded piece on which

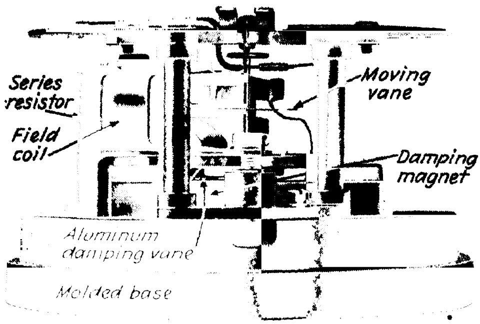


FIG. 236.—Moving-vane voltmeter. (*Courtesy of General Electric Co.*)

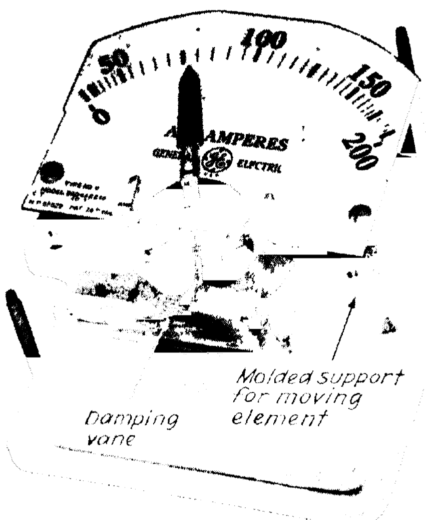


FIG. 237.—Damping vane of moving-vane ammeter. (*Courtesy of General Electric Co.*)

the movement is mounted and in the cylindrical chamber of which the vane is contained and damped (Fig. 234). The stationary coil is then slipped over the molded chamber, and the whole assembly mounted on studs (Figs. 235, 236). A tap from the

coil is often connected to the movement of a potential measuring instrument to limit its possible potential above ground.

Larger instruments of the same type require a more effective air-damping chamber. In this construction a molded insulating

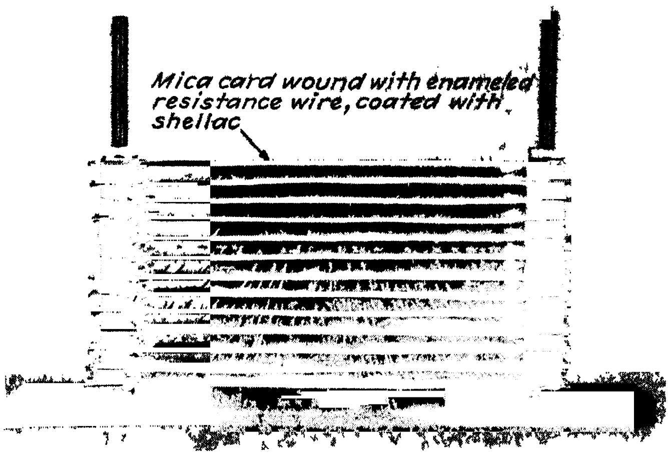


FIG 238 Card-type voltmeter resistor (*Courtesy of Westinghouse Electric & Manufacturing Co*)

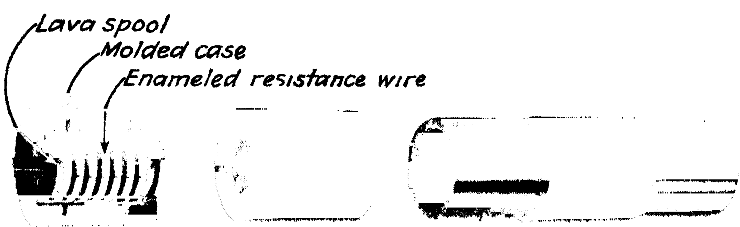


FIG 239 — Molded spool voltmeter resistor (*Courtesy of Westinghouse Electric & Manufacturing Co*)

chamber is used to mount the movement which extends through the center of the chamber. The iron vane itself then extends into the center of a molded spool under the damping chamber. On the spool the stationary coil is wound. The metal support studs are covered with insulating tubing to prevent breakdown from the stationary coil. Sometimes the damping is magnetic, using an aluminum vane passing between the poles of a permanent magnet (Fig. 237). In such instruments the molded damping

chamber is not used, but a molded case for the element movement with a coil on the outside.

INSTRUMENT RESISTOR.—Noninductive resistance becomes a necessary accessory with instruments either when a multiplier is used to measure higher voltage than that for which the instru-

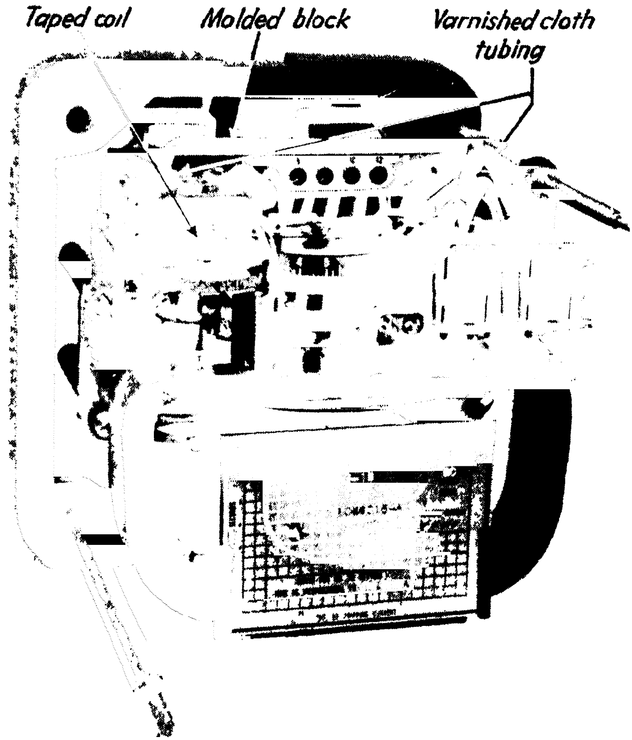


FIG. 240.—Induction-disk over current relay (*Courtesy of Westinghouse Electric & Manufacturing Co*)

ment was designed or when a high-resistance instrument is desired even for low voltages.

Such resistors are often constructed by winding fine resistance wire of nearly zero temperature coefficient on "cards" of mica (Fig. 238). These cards may be spaced and stacked together and perhaps mounted inside the meter case. An interesting construction, different from this, is shown in Fig. 239. The completed units, each good for 1,000 volts, can be assembled

with the threaded terminals to build up as many as desired. The wire is wound noninductively (one section opposite from the next) in several sections on a multiple-flanged lava spool. The spool is carried inside a molded shell which has metal ends, one a stud and the other a threaded hole. The wires are soldered to the metal

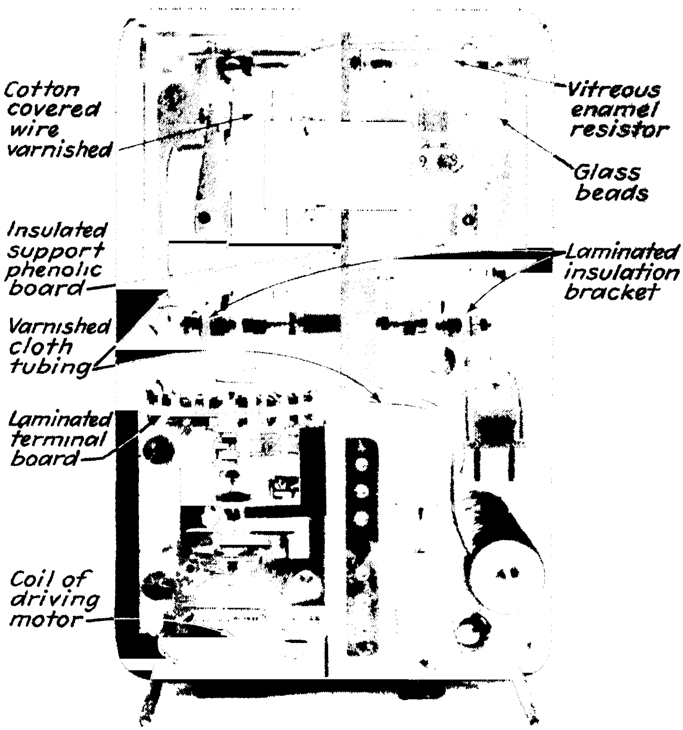


FIG. 241.—Impedance relay. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

end flanges which extend over the spool, embedded in the molded shell, to form a static shield, a point of importance if the units are built up in a stack to be used for several thousand volts.

Relays.—A relay is a device that receives an electrical impulse, usually of limited energy, and produces some desired action, often in a separate electric circuit. Some relays resemble small contactors, others have the elements of watt-hour meters, and so on. The parts are drawn from many other devices, including small

motors to produce desired motions. Bimetals, heaters, and resistors may also be used.

A base upon which to mount parts and attach the cover must contain insulation to separate the parts electrically. In some cases the whole base is made of molded insulation in which the many studs and terminals are inserted integrally. If a metal base is used, molded insulating bushings surround the studs.

Some conception of the variety of parts and their insulation can be gained from a study of Figs. 240 and 241.

CHAPTER XVII

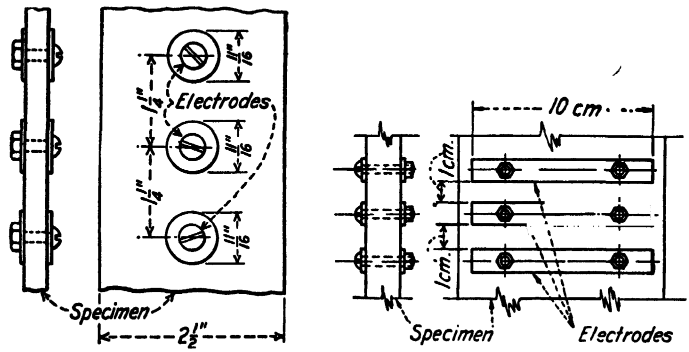
INSULATION TESTING

The testing of insulation may be carried out on samples of insulating materials or in the assembled apparatus. When tests are made on specimens, the objective is the determination of comparative properties or a means of inspection for variations in the material. Specimens are not usually the same shape as in apparatus, but often an attempt is made to select size and shape to be representative of conditions of service. For example, time-voltage tests have been devised for tape in which layers of tape are wound on a metal tube and covered with a layer of metal foil. This approximates a taped conductor. Most test specimens, however, are convenient pieces taken from the materials before fabrication. Tests on completed or partly completed apparatus are performed also for two reasons: (1) as an inspection method for passing or rejecting the product, and (2) to find out what correlation factors must be applied to tests on samples to arrive at the performance of insulation as used in apparatus.

A complete description of insulation-test methods for both materials and apparatus would require several times the present space allotted to the subject. Our purpose will be limited to a survey of the more important tests in the two fields. We wish to emphasize the importance of following reproducible and standard procedures and care in the selection and conditioning of samples. For more details on materials testing, the reader is referred to the accepted manual on this subject, the A.S.T.M. Standards on Electrical Insulating Materials, a volume of 300 pages, revised annually by Committee D-9. The testing of insulation in apparatus is another broad subject for which there are accepted standards, such as those of the American Institute of Electrical Engineers and the National Electrical Manufacturers Association.

Insulation Resistance. SERIES-VOLTMETER METHOD.—The insulation resistance of a *sample* is usually a combination of

volume resistance and surface resistance. In a cube, for example, one path is directly through the material from one face to an opposite face. There are four other paths in parallel to this, over the four surfaces of the cube. Sometimes a separation



(a) (b)

FIG. 242.—Specimens for insulation resistance tests using (a) binding post electrodes, (b) strip electrodes. (*A.S.T.M.*)

of the two components is difficult. If the total insulation resistance of plate material is desired, test specimens of material may be prepared by passing studs through the sample (Fig. 242). If surface resistance only is required, two electrodes clamped a convenient distance apart on the same side of the sample can be

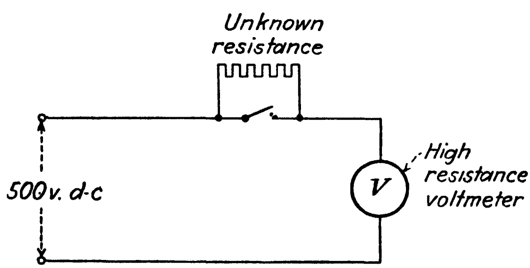


FIG. 243.—Series-voltmeter method of measuring insulation resistance.

used. Volume-resistance measurement requires a guarded electrode arrangement, in which the guard is maintained at substantially the same potential as the guarded electrode. This eliminates the error of surface conduction.

The choice of *method of measurement* will be determined by the range of resistance. If a megohm or less is to be measured, a convenient method is the high-resistance series-voltmeter

method. A voltmeter whose resistance is of the same order as that to be measured is connected in series with the specimen to a source of direct current, and a reading taken. Then the sample is shunted, and the line voltage measured (Fig. 243). If the resistance of the meter is known, the unknown can be derived from

$$R = \frac{r_2(d - d_1)}{d_1}$$

where r_2 = voltmeter resistance.
d = deflection on direct-current supply.
d_1 = deflection with R in series.

Example: If, as is common, the meter is a "megohm voltmeter" (total resistance 1 megohm) and the source is 500 volts, a reading of 250 volts with R in series would mean

$$R = 1 \times \frac{(500 - 250)}{250} = 1 \text{ megohm.}$$

For somewhat higher resistances a galvanometer and known series resistance can be used.

Two methods useful for testing surface resistance of glass or porcelain and based on charging and discharging a capacitor are of interest but are not in common use. In one, a capacitor is charged from a known potential source with the unknown resistance in parallel. After disconnecting the charging battery, the potential of the capacitor is measured after a measured time interval of discharge and the value of resistance calculated. This is known as the "loss-of-charge" method. A variation of this is the "growth-of-charge" method in which a capacitor in series with the unknown resistance is connected to a battery. A measurement of the capacitor potential at a definite time after closing the switch will permit calculation of the unknown resistance.

Direct-deflection Method for High Resistance.—A convenient circuit, approved by the A.S.T.M., is shown in Fig. 244. With switch A in the test position and switch B open, potential from the battery is applied to the sample in series with a calibrating resistor r which may be made low compared with the unknown. It is usually left in the circuit as a protection to the galvanometer in case of failure of the sample. Where great

accuracy is necessary, switch B may be closed to "short" position to shunt out the calibrating resistor. The current flowing through the sample is measured by a sensitive galvanometer used with an Ayrton multiplying shunt. For calibration of the galvanometer, switch A is thrown to "short" position to shunt the sample, and switch B is closed to the "calibrate" position.

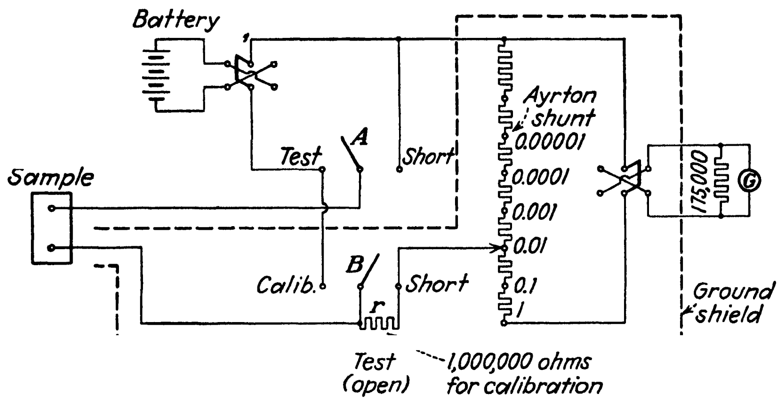


FIG. 244.—Insulation resistance circuit.

$$R = \frac{D_r}{D_R} \times \frac{\text{shunt ratio } (R)}{\text{shunt ratio } (r)} \text{ megohms}$$

where R = unknown resistance, D_r = deflection for calibrating resistance, D_R = deflection for unknown. (*A.S.T.M.*)

The battery potential is then applied to the known calibrating resistor r. A different ratio position of the Ayrton shunt is usually required for this calibration measurement. From the respective galvanometer deflections and the shunt ratios used for each, the unknown can be readily calculated. It is important, in testing samples of material where surface leakage may be appreciable, to use a guard. The switch B, the shunt, and the galvanometer terminals must also be shielded and connected to the guard.

This apparatus is also used in studying dielectric absorption. By taking successive readings of discharge current or measuring the recovery after partial discharge, the absorption characteristics of capacitors and samples of insulation can be calculated.

RESISTANCE OF APPARATUS.—The series-voltmeter method is applicable to measurement of apparatus-insulation resistance if in the range of 1 megohm or less. For higher resistance, the

"megger" is commonly used. This is a practical instrument for commercial tests in the factory or in the field. It consists of a crank-driven generator and a special indicating instrument (see Fig. 245). The current coil A is connected in series with the resistance to be measured. The coils B and B', connected in series with a resistor R, form the potential coils connected to the generator. All three coils are mechanically mounted on the pointer mechanism and move in the field of the same permanent

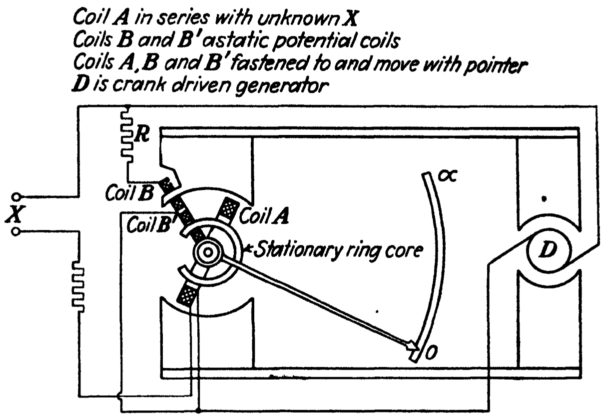


FIG. 245.—"Megger" circuit for measuring insulation resistance.

magnets as serve the generator. The coil connections are fine copper strips exerting no restoring force. A C-shaped iron piece is mounted so that coils B' and A rotate about it as a core. When the generator is operated, a current flows through the potential coils B and B'. If there is no current in coil A, the pointer and coils take up a position where the least flux from the permanent magnet poles will pass through them, which will be opposite the open portion of the C-shaped core. This will be the "infinity" end of the scale of the pointer. If current flows in coil A (a finite resistance connected to the terminals), a torque results which moves the three coils away from the slot of the central core. This movement is opposed by the increasing torque of the potential coils B and B', and the final position of the pointer and coils is a balance of the two torques. The position of balance is determined by the current in A, dependent on the external resistance being measured. The reading is independent of the generator voltage, and so great care in crank-

ing the generator at a constant speed is not necessary. Some instruments are provided with an overriding drive, so that the operator merely cranks until the clutch slips and thus maintains a reasonably constant speed. The megger is useful in checking periodically the resistance of a rotating machine or a cable to detect any deterioration or moisture absorption. Another use is in drying of machines or transformers either in the preparation for impregnation in the factory or in reclamation after a flood. Each type of machine (depending on materials and method of insulating) has its characteristic drying curve by which the progress of drying can be followed. Not the actual resistance, but whether it is going up or down and at what rate, is the criterion for judging the condition of a machine. A rule-of-thumb criterion for safe insulation resistance of railway motors, after drying, is

$$\text{Megohms} = \frac{\text{rated voltage}}{\text{rated kilowatts} + 1{,}000}.$$

Dielectric Strength.—We have discussed in another chapter the effect of several factors, such as time, temperature, humidity, frequency, and test arrangement, on the breakdown voltage of dielectrics. These comments should be recalled when interpretation and application of test data are to be made. In A.S.T.M. Test D-149, these factors are recognized in establishing standard test procedure for determining the dielectric strength of materials. The shape of sample, size of electrode, and other factors have been selected to suit the natural and convenient form of various insulations. Tests may not be wholly comparable, if the test conditions adopted for two different materials are not alike. This is not so serious, since it is not practicable to determine a value for the dielectric strength that will apply accurately under service conditions. Test values for dielectric strength usually give only some indication of insulation quality and uniformity.

A.S.T.M. SPECIFICATIONS.

Three standard methods of test,[1] with respect to the application of voltage, are in general use:

A. The Short-Time Dielectric Strength Test, in which the voltage is increased uniformly to breakdown at a specified rate.

[1] A.S.T.M. Standards on Electrical Insulating Materials, Appendix II. 1940.

B. The One-Minute, Step-by-Step Dielectric Strength Test, in which the voltage is held for one minute at a selected starting voltage, followed by one-minute steps at higher voltages, increasing successively by regular intervals (usually 10%).

C. The Endurance or Long-Time Dielectric Strength Test, in which the voltage is held either until failure or for a definitely long period of time, followed by equal periods of time at higher voltages, increasing successively by regular increments. A 30-minute endurance test is the standard procedure on taped samples of varnished cloth and 5, 15 minutes, or longer time periods up to 8 hours or more in cable practice.

Since the dielectric-strength test is perhaps the most important criterion for insulation materials, we believe it worth while to quote certain typical portions of A.S.T.M. Test D-149. This will show, first, the care with which all details have been considered and, second, the limitations of such testing. Special specimen and electrode forms have been developed for materials such as porcelain and varnishes that do not lend themselves to the general tests of D-149.

Electrodes

4. The dielectric strength of an insulating material varies with the thickness of the material and the area and geometry of the test electrodes. Tests made with different electrodes are not comparable. Where materials are made up into forms of uniform thickness, such as sheets and plates, tests shall be made upon that thickness of material. In other cases, a thickness of test specimen and diameter and shape of electrode have been selected that are compatible with convenience of testing. The electrodes used shall be as follows:

a. *Thin Solid Materials* (Sheets and Plates) (Fig. 246).
- (1) *Wide.* Metal discs 2 in. in diameter and 1 in. in length with the edges rounded to a radius of ¼ in.
- (2) *Narrow* (Tapes). Opposing cylindrical rods ¼″ in diameter with edges rounded to a radius of 1/32 in. Upper movable electrode shall weigh 0.1 ± 0.005 lb.

b. *Thick Solid Materials.* Metal disc 1 in. in diameter, and 1 in. in length with edges rounded to a radius of ⅛ in.

c. *Liquids.* Metal discs 1 in. in diameter with square edges, mounted with axes horizontal.

d. *Compounds.* Hemispherical metal electrodes ½″ in diameter.

Conditioning of Test Specimens

6. (*a*) The dielectric strength of most insulating materials varies with temperature and humidity. Usually it is desirable to determine the die-

lectric behavior of a material over the range of temperature and humidity to which it is likely to be subjected in use. As this varies for different materials reference shall be made for information concerning the conditioning treatment of a particular material to the specific method for that material. Materials may be conditioned in a suitably controlled chamber. The test specimens shall be kept in the chamber long enough to reach a uniform temperature and humidity before voltage is applied. The dielectric strength tests shall be made on the specimen while still in the conditioning chamber. For purpose of tests, a high-

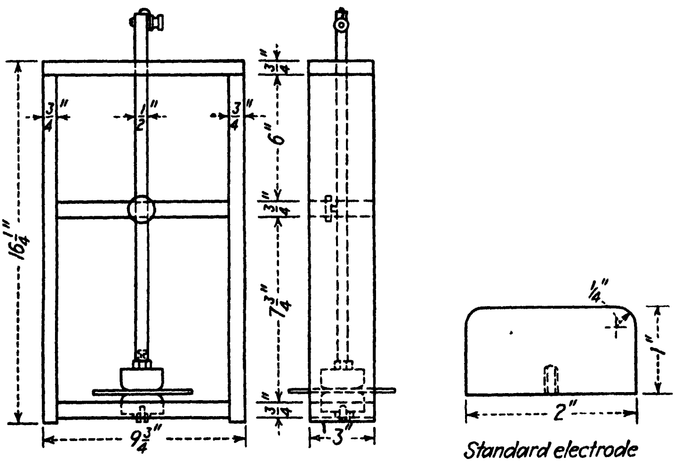


FIG. 246.—Test rig for puncture of sheet insulation.

voltage conductor may be conveniently carried into the chamber through an insulating bushing.

(*b*) For tests made in air, use may be made of any well-designed oven of sufficient size to hold the test equipment. It should be provided with some means of circulating the air, so that approximately constant temperature is maintained around the test specimen, and with a thermometer or thermocouple for measuring the temperature as near the point of test as practicable.

(*c*) For tests under oil, use may be made of an oil bath, provided with some means for circulating the oil, so that the temperature is substantially uniform around the test specimens, and with a thermometer or thermocouple for measuring the temperature as near the point of test as practicable.

Surrounding Medium for Solid Materials

7. In general, it is preferable to test materials in the medium, whether air or oil, in which they are to be used. Where conditions of use are

not well defined, materials should be tested in air up to the point where the breakdown is so high that an excessive amount of material is required to prevent flashover or excessive burning of the surface. For specimens having a high breakdown, such as the thicker and high-grade materials, it is usually necessary to make dielectric strength tests under oil. However, it should be understood that breakdown values obtained under oil are not comparable with those obtained in air. For the medium to be employed on a particular material, reference shall be made to the specific method for the material to be tested.

Application of Voltage

10. (*a*) *Short-time Test.* The voltage shall be increased from zero to breakdown at a uniform rate. For solid materials, the rate of rise shall be 0.5 or 1.0 kv. per sec., depending on the total test time required and the voltage-time characteristic of the material. For the rate applicable to a given material, reference shall be made to the test method for that material. For liquid materials, the rate of rise shall be 3 kv. per sec.

(*b*) *Step-by-step Test.* An initial voltage shall be applied equal to 50 per cent of the breakdown voltage in the short-time test, adjusted as shown in the following table:

Breakdown Voltage by Short-time Method	Adjust the 50 Per Cent of Breakdown Voltage to the Nearest
25 kv. or less	1.00 kv. (except as otherwise specified)
Over 25 to 50 kv., incl.	2.0 kv.
Over 50 to 100 kv., incl.	5.0 kv.
Over 100 kv	10.0 kv.

The voltage shall then be increased in equal increments as stated in the various material specifications, the voltage being held at each step for a definite time as stated in the specifications. The change from each step to the next higher shall be made as rapidly as possible, and the time of change included in the succeeding test interval.

Report

13. Unless otherwise specified, the report shall include the following:

(*a*) The thickness of the specimen,
(*b*) Total volts at each puncture,
(*c*) Volts per mil for each puncture,
(*d*) The average, maximum, and minimum volts per mil for each sample,

(*e*) The temperature of the test specimen,
(*f*) The percentage relative humidity of the surrounding air,
(*g*) The conditioning treatment,
(*h*) The duration of the test,
(*i*) In the step-by-step test, the value of the initially applied voltage, and the value of the voltage at each step, and
(*j*) The size and type of electrodes.

OVERPOTENTIAL TESTS.—Overpotential tests on electrical apparatus are usual for acceptance by the customer, or as a check after installation, or for test after a repair. The intention is not to damage the insulation or explore its ultimate dielectric strength but only to prove that the equipment is safe to operate at its normal voltage. Most frequently a ground test is used, *i.e.*, an overpotential between conductors and the frame or other parts intended to be at ground potential. In apparatus such as transformers and coils, we also want to ascertain whether the turn-to-turn or layer-to-layer insulation is adequate and intact. The best way to do this is to induce overpotential between turns or layers by application of higher frequencies. In some cases, such as with coils with a few turns, this may require several thousand cycles. The precautions necessary with respect to overheating by leaving high frequency on too long have already been mentioned under "Frequency," Chap. III, page 46. Approved overpotential tests are covered in the A.I.E.E. Standards.

A.I.E.E. Standard Overpotential Tests.—The rule for practically all electrical apparatus rated at 600 volts or below is to apply an inspection test of twice the rated voltage plus 1,000 volts. For apparatus rated above 600 volts, 2¼ rated circuit voltage plus 2,000 volts is applied. Railway control devices for circuit voltages lower than 125 volts are tested at 800 volts. The general rules given above apply in the case of circuit breakers up to 161 kv. circuit voltage. Above this value, the following tests are to be applied:

Circuit voltage, kv.	Dry test, kv.	Wet test, kv.
196	425	377
230	485	430
288	590	520
345	690	615

A special American Standards Association test code (C57.1, C57.2, C57.3) for transformers has some exceptions to the rules given above and should be consulted for details.

Dielectric Strength of Insulating Oil.—Breakdown tests on oil for transformers, circuit breakers, and other oil-immersed apparatus are made for three purposes: (1) as an inspection test for acceptance of purchased oil; (2) as a periodic test to determine the condition of oil in apparatus; (3) to determine whether or not used oil that has been purified is satisfactory for use.

Sampling is an important procedure and should be done with great care to avoid contamination by moisture or dirt from the sampling apparatus. Often a poor test on oil can be traced to the sampling method, rather than to the oil being tested. In particular, the entrance of moisture by condensation should be guarded against by not using bottles or containers colder than the surrounding air and not opening drums or tanks when the oil is colder than the air. The necessary precautions are covered in the A.S.T.M. Standard D-117.

The following instructions[1] for oil testing are in agreement with the A.S.T.M. Standard D-117.

Apparatus

The transformer and the source of supply of energy shall not be less than ½ kv-a., and the frequency shall not exceed 100 cycles per second. Regulation shall be so controlled that the high tension testing voltage taken from the secondary of the testing transformer can be raised gradually without opening either the primary or secondary circuit. The rate of rise shall approximate 3000 volts per second. The voltage may be measured by any approved method which gives root-mean-square values.

Some protection is desirable to prevent excessive flow of current when breakdown of the oil takes place. This protection preferably should be in the primary or low-voltage side of the testing transformer. It is not especially important for transformers of 5 kv-a. or less, as the current is limited by the regulation of the transformer.

The test cup for holding the sample of oil shall be made of a material having a suitable dielectric strength. It must be insoluble in and unattacked by mineral oil and gasoline and non-absorbent as far as moisture, mineral oil, and gasoline are concerned.

[1] Extract from "Instructions on Insulating Oil," Westinghouse Electric & Manufacturing Company.

The electrodes in the test cup between which the sample is tested shall be circular discs of polished brass or copper, one inch in diameter and having square edges. The electrodes shall be mounted in the test cup having their axes horizontal and coincident, with a gap of 0.100″ between their adjacent faces, and with the top of electrodes about 1¼″ below the top of the cup. A suitable test cup is shown in Fig. 247 and portable testing outfit in Fig. 248.

Note:

Other forms of test gaps now in use are: (1) Metal disc ½″ in diameter spaced 0.2″ apart with their axes horizontal, and (2) spheres ½″ in

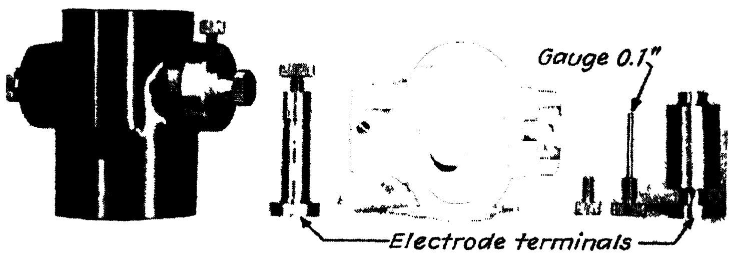


FIG. 247.—Oil test cup. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

diameter spaced 0.15″ apart with the axis of the gap vertical. If the values of dielectric strength observed with gaps of these two types are multiplied by the factors 0.55 and 0.50 respectively, the results will give the dielectric strength of the oil in the standard gap of 1″ disc spaced 0.1″ apart.

Procedure:

(*a*) The electrodes and the test cup shall be wiped clean with dry calendered tissue paper or with a clean dry chamois skin and thoroughly rinsed with oil-free dry gasoline or benzine until they are entirely free from fibers.

(*b*) The spacing of electrodes shall be checked with a standard round gauge having a diameter of 0.100″ and the electrodes then locked in position. Care shall be taken not to touch the electrodes with the gauge or in any other manner after cleaning the electrodes and cup, so as to avoid any possible contamination.

(*c*) The test cup shall be filled with dry gasoline or benzine and voltage applied with uniform increase at the rate of approximately 3000 volts (rms.) per second until breakdown occurs. If the dielectric strength is not less than 25 kv., the cup shall be considered in suitable condition

for testing the oil. If a lower test value is obtained the cup shall be cleaned with gasoline and the test repeated.

Note:

Evaporation of gasoline from the electrodes may chill them sufficiently to cause moisture to condense on their surface. For this reason, after

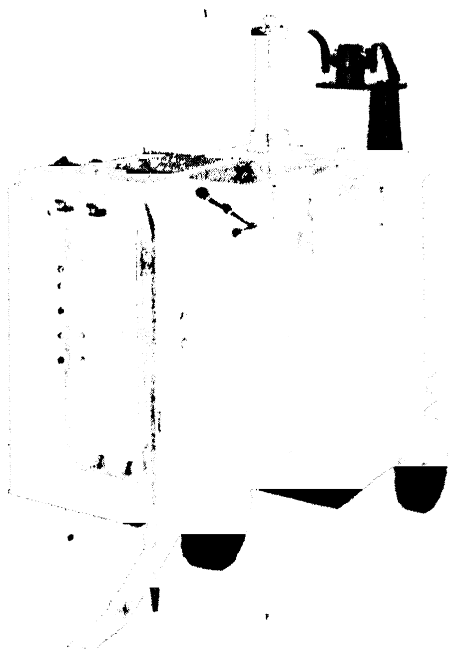


FIG. 248.—Portable oil test equipment. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

the final rinsing with gasoline, the test cup should be immediately filled with the oil which is being tested and the test proceeded with at once, or the electrodes should be thoroughly dried.

(*d*) The temperature of the test cup and of the oil when tested shall be the same as that of the room which should be between 20 and 30° C (68 and 86° F). Testing at lower temperatures is likely to give variable results which may be misleading.

(*e*) The sample in the container shall be agitated with a swirling motion to avoid introducing air, so as to thoroughly mix the oil before

filling the test cup. This is even more important with used oil than with new oil, as the impurities may settle to the bottom and the test may be misleading.

(*f*) The cup shall be filled with oil to a height of no less than 0.79″ (20 mm.) above the top of the electrodes.

(*g*) The oil shall be gently agitated by rocking the cup and allowing it to stand in the cup for three minutes before the first and one minute before each succeeding puncture. This will allow air bubbles to escape.

(*h*) Voltages shall be applied and increased uniformly at a rate of approximately 3000 volts (rms.) per second until breakdown occurs as indicated by a continuous discharge across the gap. (Occasional momentary discharges which do not result in a permanent arc may occur; these should be disregarded.)

(*i*) Provision shall be made for opening the circuit as promptly as possible after breakdown has occurred in order to prevent unnecessary carbonization of the oil. After each puncture, the testing vessel shall be jarred to loosen particles of carbon adhering to the electrodes and the oil gently agitated but not with sufficient violence to introduce air bubbles.

(*j*) Five breakdowns shall be made on each filling, after which the vessel shall be emptied and refilled with fresh oil from the original sample. The test shall be continued until the averaged values of at least three fillings do not differ from their mean by more than 10 per cent.

Report

The report shall include the volts (rms. value) at each puncture, the average voltage for each of the three or more fillings, grand average voltage, and the approximate temperature of the oil at the time of test. The diameter of the disc electrodes and the gap should also be given.

Note:

A precision of about 3 per cent may reasonably be expected in 15 tests distributed among three consistent fillings taken in succession. But if the length of the gap is readjusted and possibilities of contamination exist, the precision may be only 6 or 7 per cent. Differences as great as 10 or 12 per cent may occur between different laboratories even where the work is carefully done.

New oil should test 30 kv. or higher, and purified used oil 22 kv. or higher. Oil in apparatus testing less than 18 kv. is not considered satisfactory for further service until purified.

Dielectric Constant.—The usual method of determining the dielectric constant of a solid dielectric is to measure the capaci-

tance of a capacitor containing the unknown dielectric and compare the value with the calculated or measured capacitance, with a vacuum (or air) as the dielectric. If the capacitor is formed by two parallel plates, as in Fig. 249*a*, the total capacitance will be the sum of the true capacitance plus the edge capacitance caused by stray flux at the electrode edge, plus the capacitance of the high-voltage electrode to ground. Elimination of the latter two components can be accomplished by the use of a guard ring and a shield (Fig. 249*b*). The guard ring and guarded electrode are

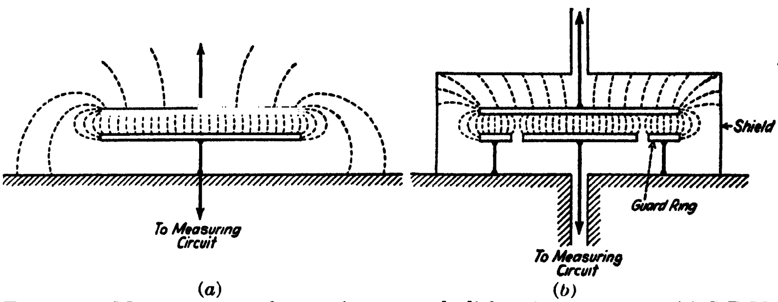


FIG. 249.—Measurement of capacitance and dielectric constant. (*A.S.T.M. Standard D*-150.)

maintained at substantially the same potential so that there is no flux passing from ring to electrode. Such a capacitor is measured by any of the capacitance bridges, such as the Schering or Atkinson.

Power Factor and Dielectric Loss. DYNAMOMETER WATTMETER.—This instrument for measurement of dielectric losses at high voltage consists of two coils, one of which is a potential coil and the other a current coil. The potential coil is connected to the high-voltage source (also applied to the sample) through a shielded resistance divider or to a low-voltage tap on the high-voltage transformer winding. The coil then is substantially at ground potential. The current coil is connected in series with the test sample, on the ground side. Usually, compensation for the phase-angle error of the potential coil is obtained by a series capacitor shunted by an adjustable resistor (see Fig. 250).

ELECTROSTATIC WATTMETER.—This is a modified quadrant electrometer in which the moving vane is connected to the high-potential source by a resistance divider or to a low-voltage tap on the transformer. The stationary quadrants are connected across

a resistor which is in series with the test sample. The potential drop across the resistor is proportional to the current through the sample. Thus the potential applied to the quadrants is a measure of the current (Fig. 251).

Both types of wattmeter require sensitive adjustments and are delicate and vulnerable to vibration. The calibration may change from day to day, and elaborate shielding is necessary to

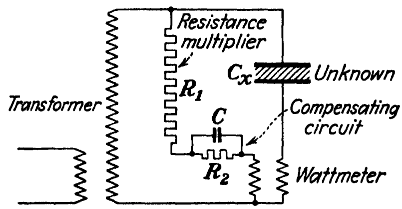


FIG. 250.—Dynamometer wattmeter circuit.

eliminate the effects of stray fields. Reliable tests can be obtained if the instrument is corrected and adjusted, with a standard no-loss condenser or a condenser of known losses. Because of the difficulty and time required in making measurements of loss with wattmeters, preference is given to bridge

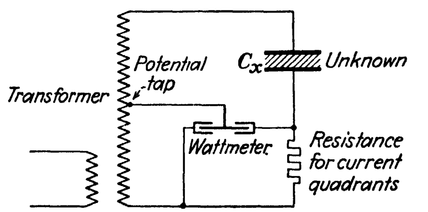


FIG. 251.—Electrostatic wattmeter circuit.

methods which are more convenient and which yield information on capacitance and dielectric constant as well.

BRIDGES.—There have been many types of bridges developed for measuring capacitance and power factor, some adapted to special problems and others for general use. The following types, bearing the names of their originators, have been in use: De Sauty, Grover, Wien, Rosa, Owen, Dawes-Hoover, Schering, and Atkinson. The last two are the bridge circuits most commonly used.

The *Schering bridge* was introduced in 1920 and has enjoyed general acceptance as having the highest sensitivity of known

circuits. Measurements have been made of power factors of 0.0001 per cent, although for commercial testing 0.01 per cent is sufficiently accurate.

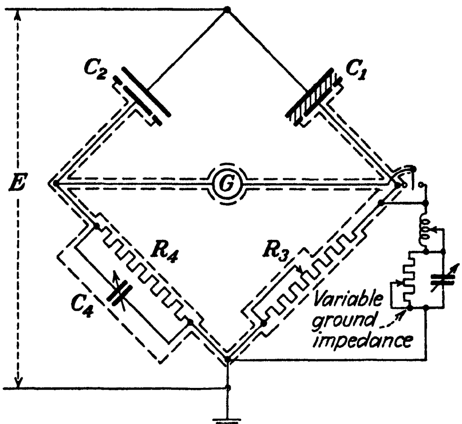


FIG. 252.—Schering bridge circuit. (*Benedict.*)

The Schering bridge circuit[1] in its simplest form is shown in Fig. 252. The branch-impedance operators may be written as

$$Z_1 = R_1 + \frac{1}{j\omega C_1};\quad Z_2 = \frac{1}{j\omega C_2};\quad Z_3 = R_3;\quad Z_4 = \frac{1}{(1/R_4) + j\omega C_4}.$$

Applying the general balance condition, $Z_1Z_4 = Z_2Z_3$, and inserting terms,

$$\left(R_1 + \frac{1}{j\omega C_1}\right)\left[\frac{1}{(1/R_4) + j\omega C_4}\right] = \left(\frac{1}{j\omega C_2}\right)(R_3).$$

Reduction of this equation gives

$$\left(R_1 - j\frac{1}{\omega C_1}\right) = \left(\frac{R_3C_4}{C_2} - j\frac{R_3}{\omega R_4 C_2}\right).$$

Equating effective resistance and reactance terms.

$$R_1 = R_3\frac{C_4}{C_2},$$

$$C_1 = C_2\frac{R_4}{R_3}.$$

[1] The discussion of Schering and Atkinson bridges is adapted from F. R. Benedict, "Measurement of Dielectric Power Factor," *Elec. Jour.*, vol. 31, p. 239, June, 1934.

The loss angle δ of the tested capacitor C_1 is

$$\delta = \tan^{-1} \omega C_1 R_1 = \tan^{-1} \omega C_4 R_4.$$

Then

$$\text{Power factor} = \cos \theta = \sin \delta \approx \tan \delta = \omega C_4 R_4.$$

The values of the known arms can be chosen so that calculation of power factor and capacitance of C_1 (the sample) is simple. When balanced, the setting of C_4 can be read directly in power factor. The detector or galvanometer for indicating balance is usually a tuned vibration galvanometer. In this instrument a soft iron vane suspended on a phosphor bronze strip is located in the fields of two coils, one a direct-current magnet that polarizes the vane and the other an alternating magnet that causes the vane to oscillate. By adjustment of the direct-current field or the tension in the suspension, the vane can be tuned to resonance at the alternating-current frequency. A mirror attached to the vane will then give a band of light covering the limits of travel. Balance of the bridge is obtained when the beam narrows to a minimum. A sensitivity of 40 mm. per microamp. at 1 m. from the mirror can be obtained.

The method of procedure in using this bridge is as follows: The balance for power factor requires two simultaneous adjustments. A null reading of the galvanometer is obtained by varying R_3 and C_4. The galvanometer is then switched to the shielding circuit and again balanced for zero reading with the variable ground impedance. The galvanometer is then switched back to the bridge position, and the R_3, C_4 balance readjusted if it has changed. The power factor and capacitance can be obtained by inserting the C_4 and R_3 terms into the power-factor and capacitance equations.

The conventional Schering bridge cannot be used with a grounded sample, such as bushings on apparatus. A modification was therefore developed.

The *inverted Schering bridge* has the ground and supply-voltage points interchanged (Fig. 253). Ordinarily in the regular Schering bridge the voltage across the (R_3) and (R_4, C_4) branches is less than 1.5 volts, and the voltage to the ground the same amount. In the inverted bridge the voltage drop across these branches is the same as in the regular Schering bridge, but the voltage to

ground is full test voltage. Accordingly, the branches must be insulated for full test voltage above ground. It has been found that 13.8 kv. is sufficient voltage to locate faulty insulation, for the curve of power factor vs. voltage is fairly flat for most commercial insulations. To eliminate stray capacitance to ground and between the arms, the shielding circuit is raised to galvanometer potential with a variable ground impedance.

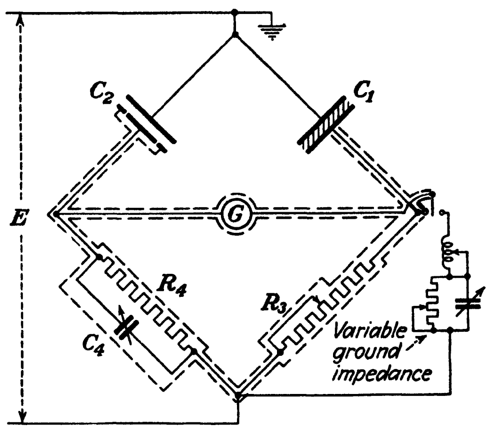


FIG. 253.—Inverted Schering bridge circuit. (*Benedict.*)

Atkinson Bridge.—In a bridge of the Schering type, it is essential to have a standard air capacitor that will operate satisfactorily at the highest voltage applied. Such condensers are bulky and costly. The elimination of this air capacitor is attained in the bridge designed by Atkinson, shown in Fig. 254, which embodies a new principle in the technique of bridge measurements. The bridge is opened at one corner, and the two halves of the resulting network are supplied at different voltages, from windings of the same transformer and in phase with each other. The voltage applied to the branches containing the test sample may be several kilovolts, and the voltage of the other side is below 300 volts and supplies the standard-capacitor branch of the network. A compensating circuit makes it possible for exact phase equality to be obtained. This bridge applies the high voltage to the test sample only and by limiting the voltage of C_2 to a low value permits a mica standard to be used. The resistances need not be insulated for high voltage and are low in ohmic

value; the possibility of residual capacitance and inductance errors is thus reduced.

POWER-FACTOR TESTS ON INSTALLED EQUIPMENT.—Means have been sought for ascertaining the "state of health" of insulation that has been in service and subject to deterioration. An overpotential test will show that the dielectric strength is at least greater than the test voltage used. The test may cause destruction of the insulation, whereas reconditioning might have been possible, had a harmless test been used. Measurement of insulation resistance is useful and nondestructive, but interpretation

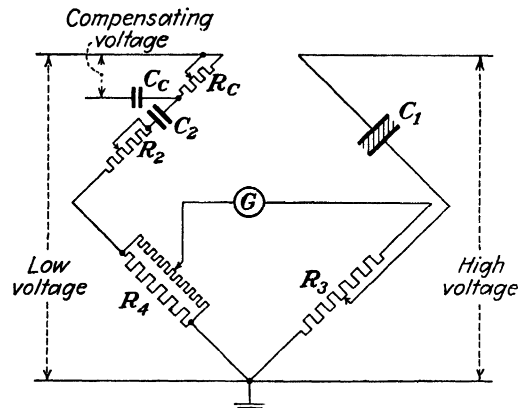


FIG. 254.—Atkinson bridge circuit. (*Benedict.*)

of results is often difficult. Resistance may be a complex factor made up of contact resistance, volume resistance, and surface resistance. The internal condition in the insulation may be indeterminate. Power-factor measurements have therefore been selected and used successfully for field testing of bushings of all types, lightning arresters, insulating oil, and transformers.

For this purpose, portable loss-measuring devices and bridges have been developed, most important of which is the indicating meter and auxiliaries used by the Doble Engineering Company, which offers an inspection service to utilities. Apparatus is tested with Doble equipment at 10 kv., 60 cycles, without being removed from its location, but disconnected from the circuit. Very convenient and rapid procedure has been developed for obtaining power factor or loss data as a periodic check on apparatus insulation. The real problem comes in the intelligent inter-

pretation of such data. When power-factor testing was first put into use by utilities, without adequate experience, much apparatus was condemned unnecessarily, and controversies with manufacturers resulted. Now, however, there is general agreement on the correlation between power-factor testing and insulation quality, at least for certain types of equipment, notably bushings. Many terminals of transformers and circuit breakers under suspicion from power-factor tests have been removed from service and reconditioned in time to prevent service outage and destruction of apparatus.

Tests have shown that a serious reduction (40 per cent) in dielectric strength of bushings which are made largely of organic material, accompanies an increase in power factor from an initial 2 per cent to a final 25 per cent at room temperature. Such an increase in power factor is most probably due to moisture absorption and if so can be brought to normal again by proper drying procedure. But there may be other causes of high power factor, such as chemical changes in materials, that may or may not be detrimental. Certain cellulosic materials, such as cellulose acetate or cellophane, have exceptional dielectric strength but rather high dielectric losses, because of their molecular structure. Oxidation of oil causes an appreciable increase in power factor, even though moisture is absent and the dielectric strength is high.

It has been noted that deterioration of organic insulation is a normal thing, regardless of type of design and care in manufacture. Tests at intervals of 1 to 2 years will uncover insulation that has reached a questionable condition, before damage has occurred. It is the practice of many operating companies to classify apparatus as "good," "deteriorated," or "remove."[1] The second classification indicates a warning but does not require immediate repair or replacement. Apparatus that has never been in use but has been kept in storage often shows high power factor, a fact usually caused by nonideal storage conditions. Moisture is almost always the cause of such cases of high power factor, and drying will restore the original condition.

The exact values of power factor (determined by the wattmeter, voltmeter, and ammeter method from tests at 10 kv. with Doble equipment) that mark the division between good and bad

[1] Gross, I. W., "Field Testing of Bushings and Transformer Insulation by the Power-factor Method," *Elec. Eng.*, vol. 57, p. 589, October, 1938.

have to be chosen with great care and correlated with other facts collected over a period of years. Illustrative are the data given by I. W. Gross,[1] based on over 5 years' experience and thousands of tests. For bushings, "good" is below 3.5 per cent power factor, deteriorated condition is evident from 4 to 7 per cent power factor, and above 7 per cent removal for repair is recommended. Considering the variety of materials involved in insulation, it is rather surprising that power-factor testing is as reliable an indicator as it has proved to be. An experimental or synthetic demonstration is often disappointing. Experimental transformers, containing a controlled amount of moisture in equilibrium, have been tested for power factor and dielectric strength. No noticeable correlation was found. In fact, from a breakdown standpoint, some moisture in cellulose materials is an improvement over the "bone-dry" state.

Other nondestructive test methods have also been used, particularly the corona and radio-noise measurements. Local insulation deterioration in apparatus will produce corona discharges at or above operating voltage. Corona will cause high-frequency oscillations that can be detected by suitable circuits and indicating devices. Standard tests have been devised for measuring radio interference or noise levels caused by high-voltage apparatus. Although the original purpose was to help radio reception, the test was found useful as a criterion of insulation quality or condition. Curiously enough, the highest radio-interference level among a number of new transformer units was found in a unit that had been made completely dry. This can be explained by the known fact that moisture helps to relieve excessive potential gradients which give rise to local discharges and radio noise. From an electrical-strength standpoint, some moisture is beneficial, both for normal-frequency and impulse tests. Experience must therefore be accumulated on the limits of "beneficial" moisture before measurements depending on moisture content only can be interpreted. Imperfect as these field-test methods are, the users are encouraged by the record of reduction in apparatus failures from insulation deterioration that they have been able to forestall.

Line-insulator Tests.—Tests on insulators are for two purposes. Those termed "design" tests are made to determine char-

[1] *Ibid.*

acteristics of the unit or group of units. Those termed "routine" tests are made for inspection of manufactured products. Except for the additional routine test using a damped 200,000-cycle

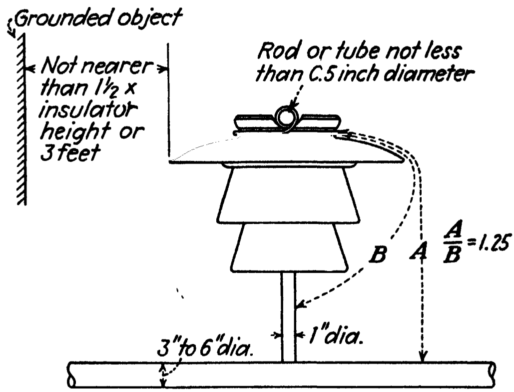


FIG. 255.—A.I.E.E. Standard test setup for flashover of pin-type insulators.

source to detect flaws in the porcelain, the design tests are similar in nature to the routine tests. The A.I.E.E. Standard 41 is the accepted procedure for electrical and other tests on insulators and should be consulted for complete details.

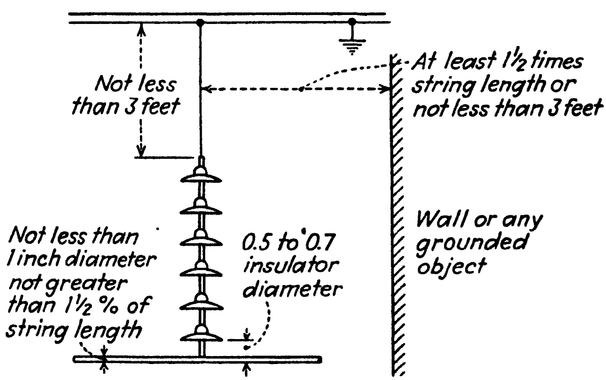


FIG. 256.—A.I.E.E. Standard test setup for flashover of suspension insulators.

The electrical tests usually made include: (1) 60-cycle dry flashover; (2) 60-cycle wet flashover; (3) critical-impulse flashover; (4) volt-time curves; (5) radio-interference test; (6) corona test; (7) puncture test; (8) combined mechanical and electrical strength (Figs. 255, 256).

POTENTIAL GRADIENT OF SUSPENSION INSULATORS.—A capacitance network, equivalent to a string of suspension insulators, will consist of the capacitances of each unit in a series relation from line to tower, the capacitances of the hardware of each unit to the tower, and the capacitances of the hardware of each unit to the line. The combined effect of these capacitances is an unequal distribution of capacitances and voltage along the string. The

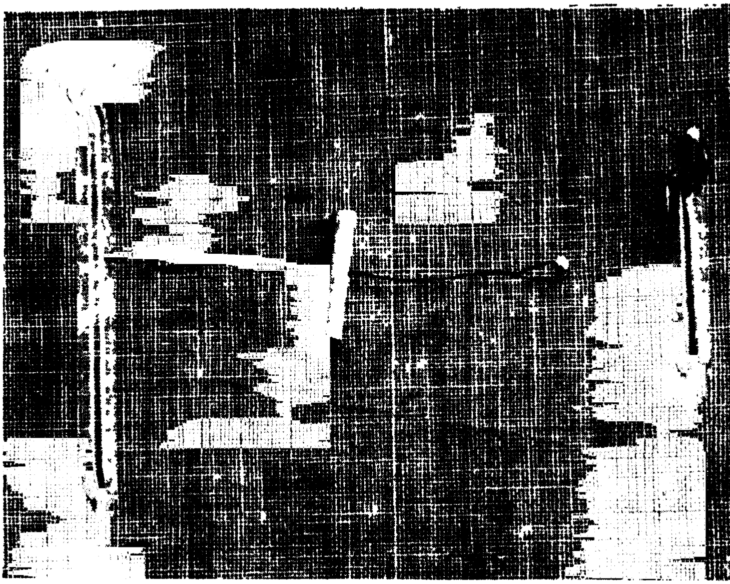


FIG. 257.—Exploring tubes and straw. (*Mulhotra.*)

line unit has the lowest total capacitance and the highest voltage drop.

Various test methods are used to determine the gradient along a string so that corrective means may be applied.

1. A *static voltmeter* for high voltage may be used to measure the drop across each unit.

2. A *potentiometer* may be connected to the line in parallel with the string, and a probe electrode connected to find a point where there is no potential difference.

3. A method for exploring both the field form around a string and the gradient was described by M. R. Mulhotra.[1]

[1] *Elec. World*, vol. 95, p. 201, Jan. 25, 1930.

The *silhouette* of an insulator string was projected on a blackboard and outlined in chalk. A piece of straw 1 in. long and ⅛ in. in diameter was suspended in the field by a thread through a hole perpendicular to the axis. The straw took up a position

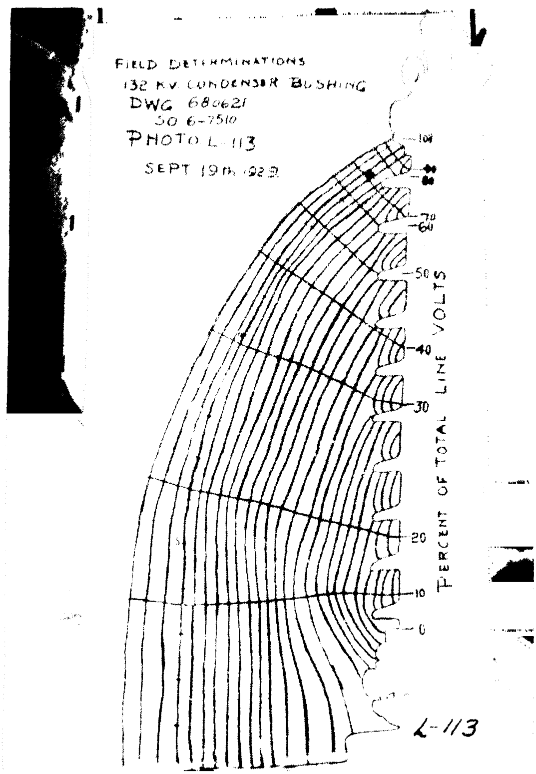


FIG. 258.—Exploration of field around bushing. (*Mulhotra.*)

parallel to the lines of force, and its shadow was traced in chalk as it was moved in the field.

Having the lines of force plotted, a small neon tube was suspended on any selected line of force, and the voltage on the insulator string raised until the tube glowed. The tube was then moved to another plotted line of force, the same voltage applied, and the tube moved parallel to the field until it glowed. This point was then on an equipotential line connecting its new position to the original position. By traversing two or more plotted lines of force an equipotential line could be drawn in. With the

same tube a different equipotential could be determined by changing the terminal voltage (Figs. 257, 258).

4. The *small spark-gap method* is more convenient than the potentiometer or static-voltmeter method. A small gap of convenient dimensions preferably with capacitance low compared with the insulator capacitance, is shunted around the first insulator. The terminal voltage is raised until the small gap sparks. Then the gap is transferred to the next insulator and the test repeated. If the gradient across the second is less than the first, a higher terminal voltage will be necessary to cause the gap to spark. This procedure is continued until a value of total string voltage is obtained for each position of the small gap. From the following explanation, it will be clear that the actual breakdown voltage of the gap does not need to be known.

Let e = breakdown of small test gap.

E = total applied voltage when test gap flashes over for any unit n.

$\frac{e}{E_n}$ = portion of total voltage E_n on unit n.

$\frac{e/E_n}{e/(\Sigma E_n)}$ = ratio of portion across unit n to total sum of portions, or (if multiplied by 100) = %.

e can be canceled from the expression,

Therefore,

$$\frac{1/E_n}{1/\Sigma E_n} \text{ or } \frac{1/E_n}{1/E_1 + 1/E_2 + 1/E_3 + \cdots 1/E_n} = \% \div 100.$$

Example:

Unit	E	Reciprocal	%
1	30	0.0333	27.2 (0.0333/0.1217)
2	40	0.025	20.6
3	50	0.02	16.4
4	60	0.0166	13.7
5	70	0.0143	11.8
6	80	0.0125	10.3
		0.1217	100.0

DIELECTRIC-STRENGTH (PUNCTURE) TEST ON PORCELAIN INSULATORS.—Porcelain suspension insulators are tested for

puncture strength in an oil bath to suppress flashover. Certain specifications for conducting the test have been established by the A.I.E.E. Standard 41, as given below. Samples taken from a lot of insulators are given the destructive puncture test to indicate the quality of the lot.

41-153 *Puncture Test.*

Puncture test shall be performed with the insulator inverted and so immersed in insulating oil that the oil will be at least 6 in. (15.24 cm.) deep over all parts of the insulator. The insulating oil shall be capable of withstanding 15 kilovolts between 1 in. (2.54 cm.) discs spaced 0.1 in. (0.254 cm.) apart.

The test shall be performed by applying voltage between the cap and stud or corresponding metal fittings and raising it at the rate of approximately 10,000 volts every 15 seconds to a value at which puncture occurs. The initial applied voltage may be raised quickly to approximately the dry flashover voltage.

In testing link-type insulators the holes may be filled with conducting material.

CHAPTER XVIII

HIGH-VOLTAGE TESTING EQUIPMENT

Oscillator (Tesla Coil).—The Tesla coil (named after its originator, who also invented the induction motor) was one of the first successful devices for producing high voltage before step-up transformers of the usual type were made. An oscillating circuit

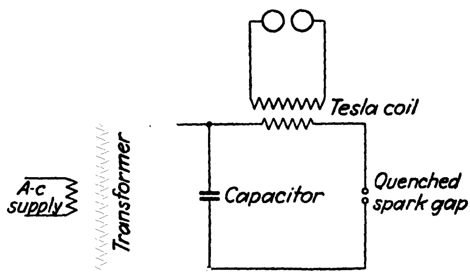


FIG. 259.—Tesla coil circuit.

with capacitance C, inductance L, and spark gap is supplied through a small step-up and isolating transformer (Fig. 259). When the potential across C is high enough, the gap will break down and current flow in the circuit. This current will be oscillatory, of a frequency determined by the expression

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{(4L^2)}} \text{ cycles}$$

where C is in farads, L in henrys, and R in ohms.

The amplitude of the current will decrease until a new train of waves is started at the next half cycle of the supply. The portion of the apparatus giving rise to the name is an air-core transformer of which L is the primary. The high-voltage winding of the Tesla coil may be connected to any object to be tested. Frequencies obtained are usually 100,000 to 1,000,000 cycles per second. As a part of the routine inspection of insulators, both assembled and as shells without hardware, damped oscillations of 200,000 cycles from a Tesla coil may be applied to electrodes

in contact with the porcelain for 1 min. to locate defective pieces. Leakage paths will heat and indicate a short circuit visually by a change in the type of discharge. A 60-cycle continuous discharge (limited in current value by resistance) is now probably more commonly used.

Testing Transformers.—The progress in designing testing transformers has been almost a process of lifting oneself by the bootstraps. For the development of high-voltage power transformers and other apparatus, 20 years or more ago, voltages

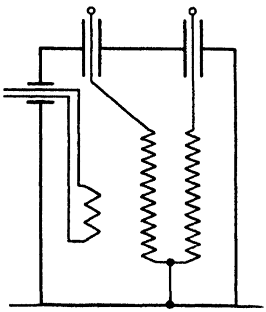


Fig. 260.—Testing transformer, mid-point of secondary grounded.

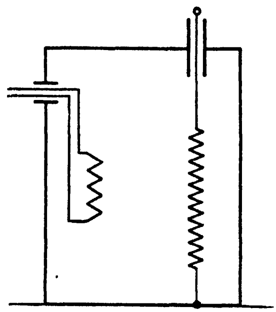


Fig. 261.—Testing transformer, one end of secondary grounded.

much in excess of apparatus ratings were required, and for research still higher potentials were sought. Testing transformers had to be built, with inadequate knowledge, in order to provide a tool to obtain the desired information. Through the construction and failure of testing transformers, much was therefore learned about insulation of high-voltage apparatus. The frequent casualties among transformers used for test purposes were therefore not in vain. By such experience, designers learned how to distribute potential gradients, to eliminate corona discharges under oil, to prevent surface creepage, and to guard against surge failure of end turns. These solutions were useful alike in power apparatus and in building testing equipment that would stand up.

Many of the early transformers were grounded in the center of the high-voltage winding and had two equally insulated terminals. The insulation with reference to the core and tank was therefore only one-half the total terminal voltage (Fig. 260). Such an arrangement produced high voltage, to be sure, but not a very

convenient or useful arrangement except for research where the objects or samples to be tested can be insulated from ground. Practically all testing is now done with one terminal grounded. A transformer is therefore needed with one end of the winding grounded to the core and tank and the other end brought out in one bushing insulated for the total voltage (Fig. 261). During the early 1920's the voltage of such grounded-terminal transformers was pushed higher and higher, until single transformers for 1 million volts were built (Fig. 262). The cost of such equipment went up faster than the voltage obtained, and the ever-present hazard of insulation failure which would require a long and expensive repair operation finally caused the race to be abandoned. Instead, an arrangement known as the "Dessauer connection" has come into common use (Fig. 263). A series, or cascade, connection of similar units can be built up to produce, rather easily, voltages much higher than those possible in a single unit (Fig. 264). Other advantages are apparent; if a failure occurs, there is no danger of "all the eggs being in one basket." The remaining transformers can be used to their capacity, and the defective unit repaired without completely shutting down the laboratory. The total investment is less, and a flexibility of connections for multiple phases or for separate, independent units is possible.

FIG. 262.—Million-volt testing transformer, one end grounded. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Supply for Testing Transformers.—Several methods of providing continuously adjustable voltage for testing transformers are available, of which three are most frequently used. A generator

with suitable field control may be used, although uniform rate of rise over the whole range is difficult by this method. Another is an induction regulator, usually 100 per cent buck or boost,

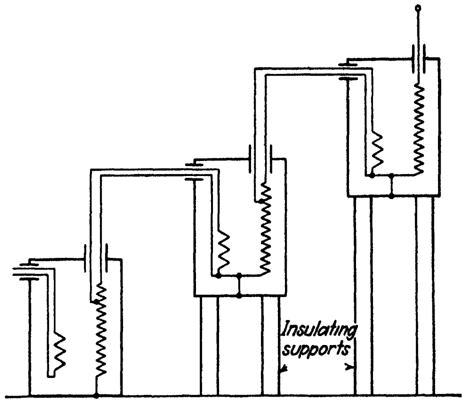


FIG 263 —Testing transformers, cascade connection.

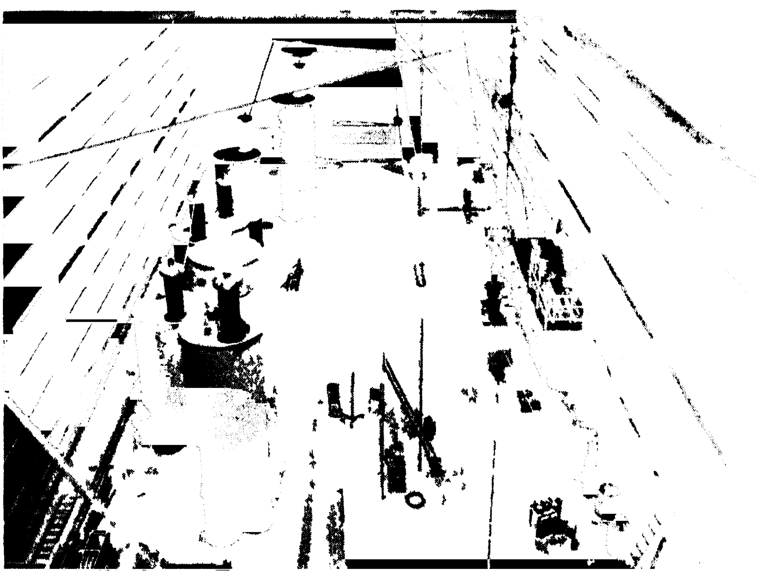


FIG 264 —Harris J Ryan High Voltage Laboratory, Stanford University, cascaded transformers. (*Courtesy of General Electric Co.*)

connected between the supply and the transformer primary. For large units, a regulating transformer is preferred, in which a multitap transformer is connected to the testing-transformer

primary. Operation of the regulator motor shifts connections to successive taps at the next higher voltage. Smooth variation between taps is obtained by a small induction regulator which is successively applied to the transformer taps by automatic switching.

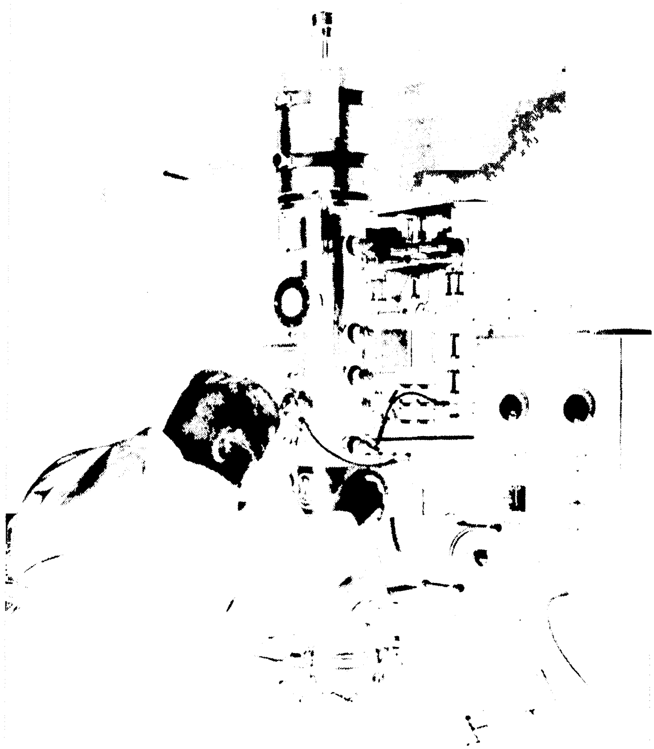


FIG. 265.—Cold-cathode type of cathode-ray oscillograph. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Voltage Measurement.—Several acceptable methods are available for measurement of alternating and impulse potentials, the choice being dependent on space limitations, accuracy desired, rapidity of reading necessary, and cost. As a measurement standard, the sphere spark gap has most general acceptance, but it is not an indicating device For alternating voltages, the tertiary voltmeter coil is probably most often used; and, for impulse voltages, the cathode-ray oscillograph is a practically

indispensable adjunct (Fig. 265). The subject of standard apparatus and methods of measuring high potentials is completely set forth in the A.I.E.E. Standard 4.

Surge Generators.—Impulse waves may be obtained from circuits connected to an alternating-current source with or without rectifiers. An early circuit devised by F. W. Peek, Jr.,[1] at the General Electric Laboratories produced useful single impulses which were the means of obtaining the early results on impulse characteristics of insulation. A high-voltage transformer fed

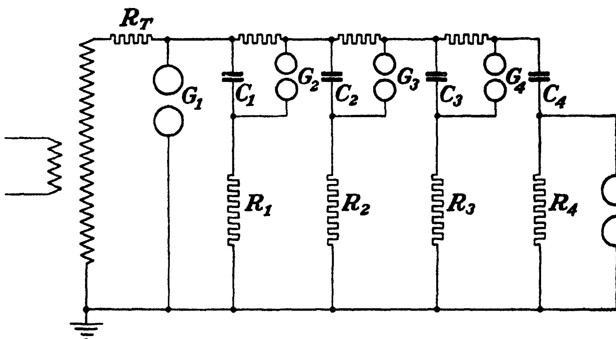


FIG. 266.—Unrectified surge generator circuit. (*Peek.*)

through high resistances a series circuit of L, C, R, and a spark gap. At the instant when the voltage was high enough to break down the gap, the capacitor discharged and produced an impulse voltage across R which was applied to the object to be tested. A later development, still using no rectifiers, placed several such unit generators in a series relation, with some modifications[2] (Fig. 266). In this arrangement, which gave as high as 5 million volts, a transformer charged the capacitors in parallel through high resistances. Each unit capacitor and charging resistor was shunted by a spark gap. An initial gap with series resistor was connected across the transformer terminals ahead of the capacitor units. Then, when this gap discharged, the transformer end of capacitor 1 was thereby grounded, gap 2 would break down, connecting the first capacitor in series with the second, and so on thoughout the set. The sparking of gap 1 would start a process

[1] *Trans. A.I.E.E.*, p. 1857, 1915.

[2] PEEK, F. W., JR., "Dielectric Phenomena in High Voltage Engineering," p. 146, McGraw-Hill Book Company, Inc., New York, 1929.

that changed (for the time of discharge) the capacitor relations from parallel to series. The resistors were high enough in value to prevent appreciable discharge of the capacitors in the time of impulse.

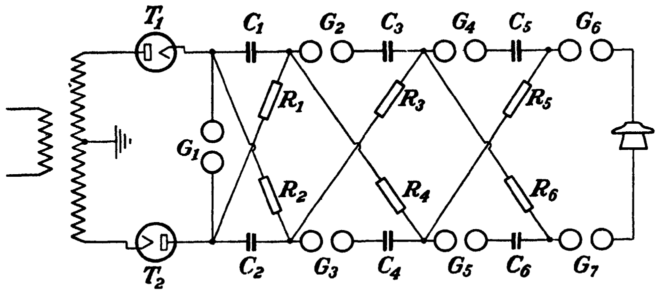


FIG. 267.—Marx circuit surge generator.

Unrectified alternating-current surge generators have been superseded by circuits employing rectifiers, because of several inherent defects of the former type. Among the disadvantages of the alternating-current generators were lack of control of: (1) wave form, (2) timing of the discharge (particularly synchronizing with a cathode-ray oscillograph), and (3) polarity.

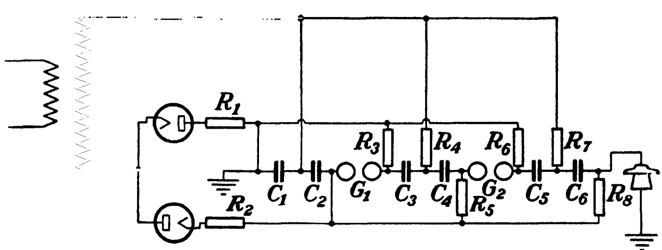


FIG. 268.—Rectified surge generator, one end grounded, three charging buses.

Most surge generators now in use are based on rectifier alternating current as a source for charging capacitors, which are switched from the parallel charging position to a series connection for adding potential on discharge. Several successful circuits were modified and developed at the Westinghouse Laboratories[1] from the Marx voltage-doubling circuit, which originated in Germany. An early elemental circuit for voltage doubling is shown in Fig. 267. A high-voltage transformer with mid-point grounded has both terminals connected through rectifying tubes T_1, T_2 to a

[1] MINER, D. F., *Elec. Jour.*, January, 1927.

spark gap G_1. Beyond and in parallel to the gap is a network of capacitors, resistors, and gaps duplicated as many times as multiples of the original charging voltage are desired. Each sectional unit adds one unit of transformer voltage E to the preceding. The action is as follows: When the potential is high enough to spark across gap G_1, capacitors C_1 and C_2 are thereby connected in series by the spark and $2E$ appears across gaps G_2 and G_3, which then connect capacitors C_3 and C_4 in series with the first two. The charging resistors are crossed between capacitors so that the polarity will be alternate and correct for addition of potential of the capacitors. The disadvantages of this circuit

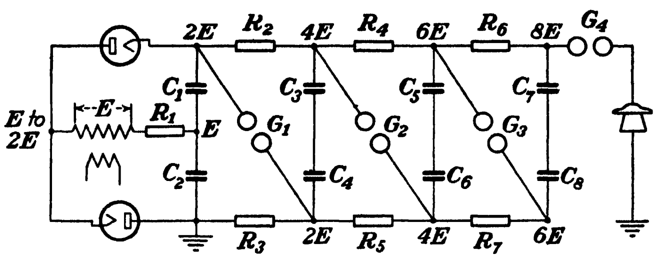


FIG. 269.—Rectified surge generator, one end grounded, series arrangement of charging resistors.

are two. The resistors are successively in series, so that the last capacitors are charged slowly. Further, it is not possible to ground either of the impulse terminals.

A circuit that corrects the first objection is that of Fig. 268. Here charging buses are used, with each capacitor charged directly instead of through the preceding resistors. But this solution, also, is not without an objection, for the resistors must each be designed for the full potential at that point, instead of merely the potential of one section.

Another connection (Fig. 269) is preferred, having a small number of gaps, easily insulated resistors, and grounding possibility. The successive series arrangement of resistors requires longer charging time for the higher capacitors, not a serious disadvantage.

Now let us take notice of the transformer insulation requirements. In the first voltage-doubling rectified circuit, the midpoint of the transformer winding is grounded, so that a minimum of insulation of winding and terminals is required. In the last two, the high-voltage winding has no fixed potential relation to

ground. One end is at unit potential E from ground, and the other end at certain times may be at a difference of E or $2E$ from ground potential. Both circuits, therefore, require a well-insulated secondary winding and adequate bushings. The unit voltage of any of these rectifier circuits is usually determined, not by transformer limitations, but by the voltage rating conveniently

FIG 270—Million-volt surge generator at Chicago Museum of Science and Industry. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

and economically obtainable for rectifier tubes. The rectifier cost goes up very rapidly with voltages above 25 kv.

Commercial surge generators are frequently built up of high-voltage metal-tank capacitor units, arranged in successive banks with the associated gaps and resistors supported on an insulating structure. Such a structure may be built up of wood, laminated phenolic plate and tubing or porcelain insulators (Fig. 270). Or the capacitors may be specially designed to combine insulating support and capacitor container, as in the General Electric surge generator exhibited at the New York World's Fair in 1939 (Fig. 271). Porcelain tubes form the columns containing capacitor units inside. The generator is built in two units, of 5 million volts each. A unit consists of 17 sections, with three capacitors each. Rating of individual capacitors is 100 kv., 0.33 μf. Charg-

ing energy is furnished at 300 kv. through kenetron rectifiers. The columns of capacitors in each group are arranged in a hexagon with the interstage gaps in the center.

ARRESTED DISCHARGE.—Something of the progressive nature of air breakdown can be learned from an interesting investigation

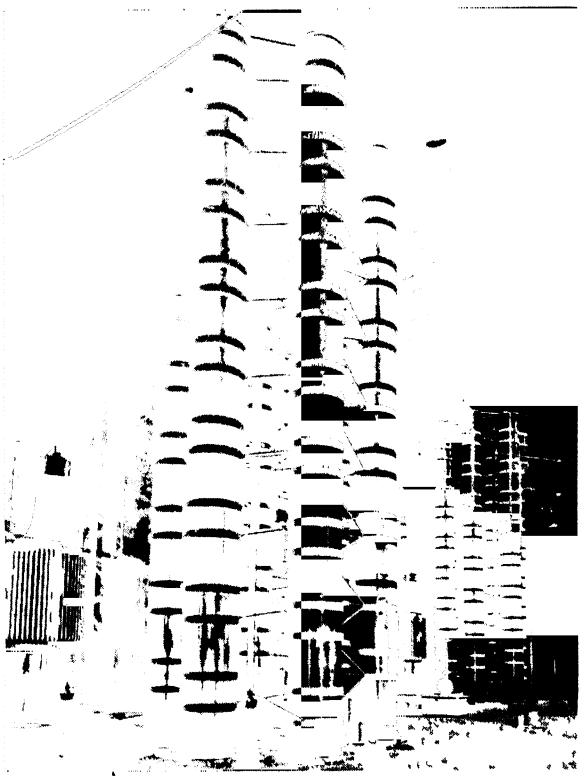


FIG. 271.—Ten-million-volt surge generator at New York World's Fair, 1939–1940. (*Courtesy of General Electric Co.*)

by J. J. Torok[1] carried out under the author's direction at the Westinghouse High-voltage Laboratory. Two parallel discharge paths can be connected to a surge generator with sufficient delaying inductance between so that the time of breakdown of the two gaps or devices are a few microseconds apart. When an impulse is applied, the first gap starts to spark, but the arc is not completed because the second gap sparks and removes the potential.

[1] A.I.E.E., vol. 49, p. 349, 1930.

By careful timing the streamers can be made to progress to different stages prior to bridging the complete gap. The phenomenon can easily be seen with the eye and recorded by the camera (Fig. 272).

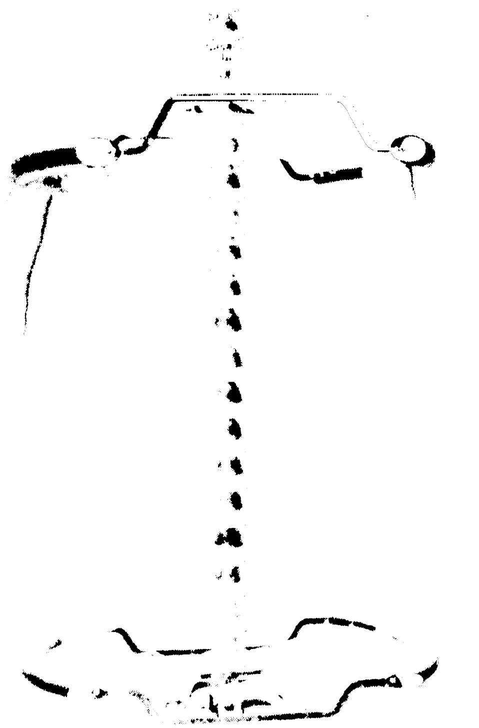


FIG. 272.—Arrested surge flashover of suspension insulators with arcing rings. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

HIGH-VOLTAGE AND -CURRENT SURGE EQUIPMENT.—After the development of rectified surge generators had proceeded to a point where controlled waves with crests of several million volts were obtainable, information gathered in field studies showed that high current discharges are present and cause damage to apparatus during lightning storms. Laboratory equipment was therefore set up to store energy in large capacitor groups at relatively moderate potentials. Surge currents of 250,000 amp.[1] or more

[1] MCEACHRON, K. B., and J. L. THOMAS, *Gen. Elec. Rev.*, vol. 38, p. 126, March, 1935.

were obtained, and the destructive effect on insulation was studied. But a combination of high voltage and high current would better reproduce the effect of natural lightning. An ingenious network was devised by P. L. Bellaschi[1] in which a surge is initiated from a high-voltage bank of capacitors and the discharge releases a high-current impulse from a separate low-voltage high-current bank of capacitors. By such means, surges of several million volts accompanied by currents of several hundred thousand amperes can be developed.

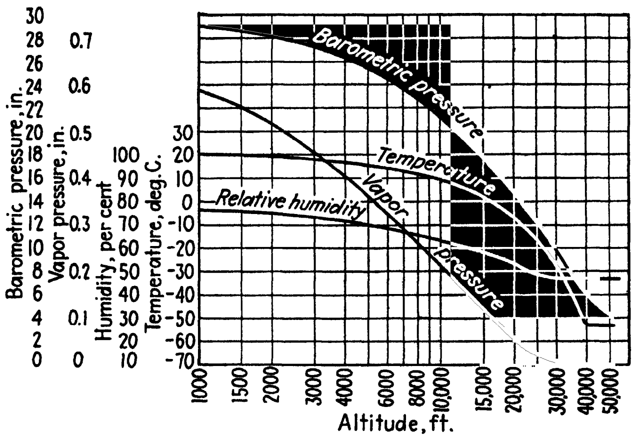


FIG. 273.—Typical weather data for upper air over the Atlantic ocean. (*U. S. Weather Bureau*, 1907.)

Surge testing, to be of engineering value and to be comparable with work in other laboratories, must be carefully planned and executed. The conditions of test, characteristics of equipment, and refinement of measuring devices must be much more completely controlled than in 60-cycle alternating-current testing of insulating materials or apparatus. During the years of development, the discrepancies between laboratories were irreconcilable, and standardization seemed impossible. In fact, a secondary standard of voltage measurement was established—the rod gap. Different experimenters could not obtain similar results in terms of voltage breakdown, but each could compare a given test with his own test on a simple gap made of blunt-ended metal rods ½ in. square. Test results were then expressed in terms of spacing of an equivalent rod gap.

[1] BELLASCHI, P. L., *Elec. Jour.*, vol. 33, p. 273, June, 1936.

Remarkable improvement in testing technique has been made, but still there are many critical factors in obtaining reliable results. Through cooperative study, a report "Recommendations for Impulse Testing," was presented to the American Institute of Electrical Engineers in January, 1940, by a joint committee of the Edison Electric Institute and the National Electrical Manufacturers Association. This report reflects the best laboratory methods known and proved by use.

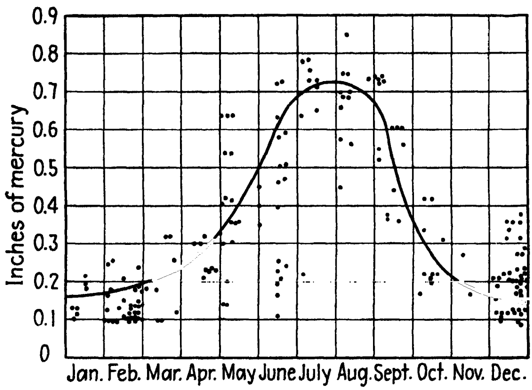


FIG. 274.—Humidity variations at Westinghouse High-voltage Laboratory, Trafford, Pa. (1938). (*McAuley.*)
NOTE: Inches of mercury × 10.7 = grains per cu. ft.

Corrections.—Tests at high voltage in air (either at normal frequency or with impulse waves) are affected appreciably by certain variables, and corrections to standard conditions should be made. The three most important variables are air pressure, temperature, and humidity. The methods of calculating correction factors are given in the standards previously mentioned. In general terms, we may say that for 60-cycle tests:

1. Flashover voltage varies directly with barometric pressure.

2. At a given location, variations greater than 5 per cent are rare, but decrease with higher altitudes is marked. Figure 273 shows typical weather-bureau data. At 3,300 ft. above sea level, the pressure is reduced 10 per cent, and at 10,000 ft. it is reduced 30 per cent.

3. Flashover varies inversely as the absolute temperature. If 25°C. is taken as standard, flashover is 20 per cent higher at −30°C.

4. Flashover varies directly with absolute humidity. For example, the humidity at Pittsburgh varies during the year from a minimum in winter of 0.1 in. mercury vapor pressure to a

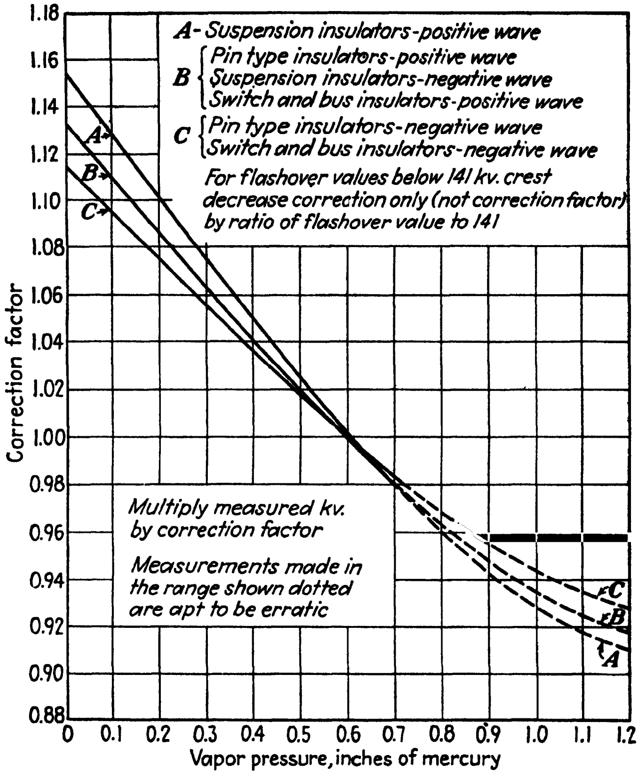


FIG. 275.—Humidity correction factors for impulse tests on insulators. (*A.I.E.E. Standard* 41.)

maximum in summer of 0.8. Corrections for this range may be as high as 20 per cent (Figs. 274, 275).

5. Low humidity and low temperatures usually occur simultaneously, and the corrections tend to cancel.

APPENDIX A

PROPERTIES OF INSULATION

Data and curves on the properties of insulating materials have been collected here for ready reference. Much of the information is correlated with the description of materials in Chap. IV and the behavior of materials under varying conditions, Chap. III. It was left out of those chapters for two reasons: (1) The thread of the description might be lost if tables of figures and curves were interspersed to interrupt the text and obscure the ready comparison of two or more materials. (2) There may be an advantage in bringing together similar data in one place where specific figures are sought, rather than thumbing through several pages of text to locate tables and curves.

The material is arranged as follows:

General properties of dielectrics.
Plastics.
Molded plastics (phenolic).
Phenolic rods, channels, angles.
Laminated resin tubing.
Laminated phenolic plate.
Cements and compounds.
Ceramics.
Fiberglas.
Magnet-wire dimensions.
Resistivity of laminations.
Specific heat and gravity of insulation.
Papers and fabrics, treated and untreated.
Insulation clearances.
Impulse tests on transformer insulation.
Breakdown curves.
Moisture in insulation.

TABLE XXIV.—PROPERTIES OF DIELECTRICS

Material	Dielectric constant	Dielectric strength, kv./cm	Thickness of sample	Resistivity, ohm-cm	Power factor, %		
					60 cycles	1 kilocycle	1 megocycle
Gases							
Air	1 0006	30 0	25 mm				
CO_2	1 0009	36 0	25 mm				
N_2	1 0005	34 8	25 mm				
H_2	1 0003	26 1	25 mm				
He	1 0007						
Liquids							
Transformer oil	2 13	135 0	0 1 in	7×10^{12}	0 5 to 2 0	0 5 to 1 5	
Castor oil	4 67	130 to 190					
Linseed oil	3 35	80 to 180					
Tung oil	3 20	30 to 40	0 1 in	8×10^{10}			
"Pyranol"	4 50	110		3×10^{12}	0 3 to 14 0		
Pine oil	1 80						
Amyl alcohol	17 0						
Ethyl alcohol	26 0			$0\ 1 \times 10^{6}$			
Methyl alcohol	33 0			$0\ 3 \times 10^{6}$			
Toluene	2 51						
Benzol	2 29	65		14×10^{12}			
Turpentine	2 23	110 to 160					
Carbon tetrachloride	2 24			25×10^{16}			
Gums							
Shellac	2 5 to 4 0			1×10^{16}	2 5		9 0
Paraffin	2 1	160 to 215	0 1 in	10^{16} to 10^{18}			
Asphalt	2 68	140	2 mm				
Waxes							
Beeswax		620 to 860	0 2 in	5×10^{14}			
Plastics							
Vinyl	4 0	80 to 200		10^{14}		1 43	1 75
Phenolic	4 8	75 to 180		$0\ 1 \times 10^{10}$ to $1\ 0 \times 10^{10}$	4 to 20	4 to 20	3 to 10

Material	Dielectric constant	Dielectric strength kv /cm	Thickness of sample	Resistivity ohm-cm	Power factor, %		
					60 cycles	1 kilocycle	1 megocycle
Plastics (*Continued*)							
Casein	4 3 to 8 3	160 to 280					5 2
Acrylic	2 8 to 3 0	190		10^{12}	2 0	2 0	2 0
Urea	6 0	75 to 150		2×10^{7}	7 0		3 0
Cellulose acetate	5 0 to 7 0	34		$4\ 5 \times 10^{1}$	15 3	7 7	5 7
Cellulose nitrate	6 7 to 7 3	75 to 250		2×10^{10}	6 2 to 14 4		7 4 to 9 7
Ethyl cellulose	3 9	400 to 500			0 25 to 2 0		
Minerals							
Asbestos		40	1 0 mm				
Quartz	3 4 to 5 1	560		2×10^{14} to 2×10^{16}	0 4	0 2 to 0 4	0 2 to 0 3
Silica	3 8	560		10^{14} to 10^{17}	0 4	0 2 to 0 4	0 2 to 0 3
Marble	7 0 to 9 0	178	25 mm	10^{9} to 10^{11}	4 to 5	3 to 4	
Mica	7 0 to 7 3	1 500 to 2 200	2 5 mm	2×10^{13} to 2×10^{17}	0 3	0 2	0 2
Soapstone	6 5 to 8 0	64	25 mm	10^{10}	1 3	0 9 to 1 2	0 7 to 0 9
Slate	6 0 to 8 0	20 3	25 mm	10^{8}	1 0	0 8 to 0 9	
Ceramics							
Crown Glass	6 2	36	25 mm	10^{14} to 8×10^{14}	1 0		
Flint Glass	7 0	75	25 mm	2×10^{14}	1 4		
Mycalex	7 5	124	2 5 mm	$8\ 6 \times 10^{11}$			0 1
Porcelain	6 5 to 7 5	70	25 mm	3×10^{14}	21 0		
Lastics							
Rubber (hard)	2 0 to 3 0	160 to 500	2 to 5 mm	10^{16} to 10^{18}	1 0	1 0	0 5 to 0 9
Gutta percha	3 3 to 4 9	80 to 200	2 mm				
Fibers							
Manila paper	2 0	25	0 2 mm				
Beeswaxed paper	2 0	770	0 2 mm				
Varnished paper	2 0	100 to 250					
Paraffined paper	2 0	500					
Varnished cotton	2 0	80 to 300	0 2 mm				
Varnished linen		100 to 200	0 2 mm				
Wood (natural)	2 5 to 6 8	50 to 300	25 mm	4×10^{3} to 6×10^{10}			
Wood (oil impregnated)	2 5 to 5 0	50 to 300	25 mm	4×10^{15}			

TABLE XXV —PROPERTIES OF PLASTICS*
(Data from "Modern Plastics Catalogue-directory," 1939)

Property	Phenol formaldehyde					Phenol furfural molding compounds		Urea formaldehyde molding compounds alpha cellulose filler	Vinyl chloride and acetate, no filler
	Molding		Laminated						
	Wood flour filler	Macerated fabric filler	Paper base	Fabric base	Asbestos base	Wood flour filler	Fabric filler		
Specific gravity	1 25 to 1 52	1 37 to 1 40	1 30 to 1 40	1 30 to 1 40	1 55 to 1 80	1 30 to 1 40	1 30 to 1 40	1 45 to 1 50	1 34 to 1 36
Specific volume cu in /lb	22 2 to 18 2	20 2 to 19 8	21 3 to 19 1	21 3 to 19 1	17 8 to 15 0	21 3 to 19 8	21 3 to 19 8	19 1 to 18 5	20 7 to 20 4
Tensile strength, lb /sq in	4 000 to 11 000	6 500 to 8 000	7 000 to 18 000	8 000 to 15 000	7 000 to 17 000	6 000 to 11 000	6 500 to 8 000	9 000 to 12 000	8 000 to 10 000
Compressive strength lb /sq in	16 000 to 36 000	20 000 to 32 000	20 000 to 40 000	20 000 to 44 000	18 000 to 45 000	28 000 to 36 000	26 000 to 30 000	24 000 to 35 000	
Flexural strength, lb /sq in	8 000 to 15 000	10 000 to 13 000	13 000 to 30 000	13 000 to 30 000	10 000 to 35 000	8 000 to 15 000	10 000 to 13 000	10 000 to 13 000	10 000 to 13 000
Thermal conductivity 10^{-4} cal /(sec) (sq cm) (deg C) (cm)	4 to 12	3 to 5	5 to 8	5 to 8		3 5 to 5	5 to 8	7 1	4 0
Thermal expansion 10^{-5}/deg C	3 7 to 7 5	2 to 6	1 7 to 2 5	1 7 to 3 0	1 7 to 2 5	3 0	4 5	2 5 to 3 0	6 9
Limiting temperature deg F continuous	350	250 to 350	212 to 300	212 to 350	400 to 450	280 to 400	280 to 350	160	
Tendency to cold flow	None	None	None	None	None	None	None	None	Slight
Breakdown voltage 60 cycles instantaneous volts/mil	300 to 500	300 to 450	400 to 1 300	150 to 600	60 to 150	400 to 600	200 to 500	650 to 720	650
Dielectric constant 60 cycles	5 to 12	5 to 10						7 to 8	
Dielectric constant 1 million cycles	4 5 to 8	4 5 to 6	3 6 to 5 5	4 5 to 7 0		6 0 to 7 5	5 0 to 7 5	6 0	4 0
Power factor 60 cycles	0 04 to 0 30	0 08 to 0 30						0 040 to 0 048	
Power factor 1 million cycles	0 035 to 0 1	0 04 to 0 1	0 02 to 0 05	0 02 to 0 08		0 035 to 0 1	0 035 to 0 1	0 01 to 0 03	0 018
Water absorption per cent after 24 hr immersion	0 2 to 0 6	1 0 to 1 3	0 3 to 9 0	0 3 to 9 0	0 3 to 2 0	0 2 to 0 6	0 8 to 1 4	1 to 2	0 05 to 0 15

Property	Methyl methacrylate molding compound	Styrene resin	Shellac molding compound	Casein resin	Cellulose products			
					Ethyl cellulose molding compound	Cellulose acetate sheet	Cellulose acetobutyrate	Cellulose nitrate
Specific gravity	1 18 to 1 19	1 05 to 1 07	1 1 to 2 7	1 35	1 14	1 27 to 1 37	1 20 to 1 22	1 35 to 1 60
Specific volume cu in /lb	23 4 to 23 2	26 3 to 25 8	25 2 to 10 3	20 5	24 3	21 8 to 20 2	22 8 to 23 1	20 5 to 17 3
Tensile strength lb /sq in	4 000 to 6 000	5 500 to 8 500	900 to 2 000	7 600	6 000 to 9 000	6 000 to 11 000	3 700 to 6 800	5 000 to 10 000
Compressive strength lb /sq in	10 000 to 15 000	13 000 to 13 500	10 000 to 17 000		10 000 to 12 000	4 000 to 16 000	11 300 to 20 300	
Flexural strength lb /sq in	10 000 to 15 000	6 500 to 8 000			9 000 to 10 000		5 600 to 11 900	
Thermal conductivity, 10^{-4} cal / (sec) (sq cm) (deg C) (cm)		1 9			5 6	5 4 to 8 7	7 7	3 1 to 5 1
Thermal expansion 10^{-5}/deg C	8 to 9	7 to 8		8	10 to 14	14 to 16	13 to 15	12 to 16
Limiting temperature deg F continuous	120 to 140		150 to 190		140 to 180	140 to 180	140 to 200	140
Tendency to cold flow	Slight	Slight	Slight		Slight	Slight	Slight	
Breakdown voltage 60 cycles instantaneous volts/mil	500	500 to 700	200 to 600	400 to 700	1 500	800 to 2 500		600 to 1 200
Dielectric constant 60 cycles	3 0 to 3 1	2 6	3 to 4			3 5 to 7 5	3 6	6 7 to 7 3
Dielectric constant 1 million cycles	3 1 to 3 3	2 6		6 15 to 6 8	2 0 to 3 0	3 0 to 5 0	3 6	6 15
Power factor 60 cycles	0 05 to 0 06	0 0003	0 004 to 0 04			0 02 to 0 07	0 014	0 06 to 0 15
Power factor 1 million cycles	0 02 to 0 03	0 0001		0 052	0 007 to 0 03	0 04 to 0 09	0 018	0 07 to 0 10
Water absorption per cent after 24 hr immersion	0 4 to 0 5	Negligible		7 to 9	1 25 (48 hr)	1 5 to 3 0	0 8 to 1 1	1 0 to 3 0

* Properties are approximate and not always comparable because of different test methods and specimen size.

TABLE XXVI.—PROPERTIES OF PHENOLIC MOLDED PRODUCTS
(Westinghouse data)

No.[a]	Specific gravity	Brinell hardness[b]	Limiting temp.,[c] deg. C.	Water absorption[d]		Mechanical strength[e]						Dielectric strength, volts/mil[l]	Dielectric constant		Power factor		Volume resistivity, 10^{10} ohm-cm
				Weight, % loss after drying	Weight, % gain after 48 hr.	1,000 lb./sq. in.			Deflection[i]	Modulus of elasticity, 10^{-5}[j]	Impact resistance, ft.-lb.[k]		At 10^3 cycles	At 10^6 cycles	At 10^3 cycles	At 10^6 cycles	
						Tensile[f]	Compression[g]	Flexural[h]									
1	1.38 to 1.40	45	125	0.75	1.00	7.5 to 8.5	26 to 30	9 to 12	0.050	10	0.60	325 to 400	7.1	5.8			1
2	1.36 to 1.42	30 to 45	125	0.70 to 1.15	0.40 to 1.10	5.9 to 8.5	20.5 to 30	9 to 12	0.045 to 0.057	10	0.50 to 0.60	325 to 400	7.5	6.0			1
3	1.89	48	150	0.49	0.20	6.2	23	11	0.027	22	1.25	200	2.7	6.8	46	13	10
4	1.91	48	150	0.35	0.15	6.7	16.7	8.8			0.79	230	24	6.7	.	10	
5	1.92	46	200	0.46	0.26	6.5	21.7	8.1			0.71	185					
6	1.89	34	150	0.28	0.13	4.5	14.4	6.5	0.016	22.5	1.13	250				2.5	
7	2.01	40	175	0.29	0.09	3.7	19.8	7			0.50	300				4.5	
9	1.50	27	125	1.07	1.79	6	16.1	8.5			2.25	250					
10	1.35	38	125	2.20	1.22	7.6	22.6	11	0.070	8.7	3.0	325				1	
11	1.38	42	125	0.73	0.71	7	27.2	10.5	0.046	24.9	0.90	250					
12	1.37	38	125	0.83	0.53	6.9	28.5	9.1	0.048	22	0.90	250					
13	1.36	50	125	1.16	0.51	6.2	30.6	10.3	0.051	21	0.80	325					
14	1.37	40	125			6	25.6	9	0.046	25	0.88	290					
15	1.35		125														
16	1.39	42	125	0.77	1.15	6.2	19.3	10	0.052		2.83	400					
17	1.35	45	125	0.61	0.36	6.3	30	10.3	0.050	10	0.55	400				20	
18	1.89	42	110	0.01	0.09	4	12.2	6.8	0.020	23	0.50	400					

[a] Numbers correspond with description in Chap. IV, p. 98.
[b] Brinell hardness figure of 10 mm. ball, 500 kg load.
[c] Temperature given is approximate only. Heat-treatment will increase some values by 25°C. for short periods or intermittent service. Some reduction in mechanical strength follows at higher temperatures.
[d] Water absorption test, A.S.T M. D48-37; 4 in. diameter disk, ⅛ in thick.
[e] The minimum mechanical strength of parts of commercial design may be 40 per cent below the values shown in this table.
[f] Tensile strength test, A S.T.M. D48-33; ¼-in. section. Many higher values given by various suppliers are obtained on 1937 revision of test permitting the use of ⅛-in. specimen. The ⅛-in. section results in higher values—as much as 20 per cent more than with the ¼-in. specimen
[g] Compressive strength, A S.T M. D48-37.
[h] Flexural strength, A.S.T.M. D48-37.
[i] Deflection (in flexure) maximum on ½ by ½ in. spacing, 4 in (A S.T M. D48-33).
[j] Modulus of elasticity (in flexure).
[k] Impact resistance: Charpy or simple beam in foot-pounds per inch of notch (A.S.T.M. D256-34).
[l] [illegible]

TABLE XXVII.—LAMINATED RESIN TUBING

Material number	Color	Constituents	Description	Application	Cost relation	Specific gravity	Ultimate strength, lb./sq. in.		Dielectric strength, 1/16-in. wall, volts/mil		Water absorption, % increase in wt. after 24 hr. in water	Power factor, 10^6 cycles 20°C.
							Tensile	Compression	In oil	In oil after 24 hr. in water		
1	Tan	Kraft paper and synthetic resin	Cannot be threaded	For mechanical or electrical use under dry conditions	Cheapest synthetic resin type	1 29	10,000	11,000	700	500	7	
2	Tan	Kraft paper and synthetic resin	Better than 1	Where machining qualities are desirable	Somewhat more expensive than 1	1.29	11,000	20,000	1,000	800	3	Less than 3
3	Brown	Kraft paper and shellac	Will collapse at 100°C. Resists arcing slightly more than synthetic resin materials. It is not baked	For general use under 75°C. except brush-holder tubes	Cheapest grade of Kraft paper and shellac insulation	1 12	8,000	7,000	800	. . .	55	
4	Brown	Kraft paper and shellac	Will not collapse at 100°F. Resists arcing slightly more than synthetic resin materials	For general use from 75 to 100°C.	Slightly higher in cost than 3	1 12	8,000	8,500	800	500	30	
5	Black	Kraft paper and synthetic resin	Similar to 2 except in color, lower dielectrically	Machinability not so good as that of 2	Somewhat less expensive than 2	1 29	11,000	20,000	650	500	3	Less than 3
6	Brown	Express paper and shellac	Will collapse at 100°C. unless supported	For tank liners	Cheapest Micarta tubing							
7	Tan	Cotton and synthetic resin	Fine-weave fabric. Has low moisture absorption	Where high impact is desired	High cost	1.25	5,800	22,000	350	. . .	2.5	

TABLE XXVII.—LAMINATED RESIN TUBING.—(*Continued*)

Material number	Color	Constituents	Description	Application	Cost relation	Specific gravity	Ultimate strength, lb./sq. in.		Dielectric strength, $\frac{1}{16}$-in wall, volts/mil		Water absorption, % increase in wt. after 24 hr in water	Power factor, 10^6 cycles 20°C.
							Tensile	Compression	In oil	In oil after 24 hr. in water		*
8	Tan	Cotton and synthetic resin	Coarser weave fabric than 7. Below 1 in. use 7	Supplied only in 1 in i.d. and above	10% cheaper than 7	1.25	6,500	15,000			6	
9	Tan	Sulphite paper and synthetic resin	Good mechanical properties. Does not punch. Best electric material for humid conditions Best paper base for heavy walls	General electrical use under humid condition	More expensive than 2	1.32	7,500	10,000	750	650	2	Less than 3
10	Tan	Cotton and special synthetic resin	Hard dense material. Special tungsten carbide tools required for machining	Light-duty bearings of 360-deg. segment only	High fabrication cost							
11	Tan	Sulphite paper and synthetic resin	Best punching material. Good machining. Not made in wall thickness over ⅛ in.	For radio-coil forms only	Most expensive paper tubing	1.32	7,500	10,000	650	550	3	3.2
12	Tan	Asbestos cloth and synthetic resin	Primarily for good heat resistance	Welding electrode insulation	Fairly expensive							
13	Tan	Asbestos cloth and synthetic resin	Somewhat inferior to 12	Primarily for good heat resistance	Cheaper than 12 tubing							
14	Tan	Cotton and synthetic resin	Fine-weave fabric Lowest moisture absorption and best for chemical application	Lower in strength than 7	High cost							

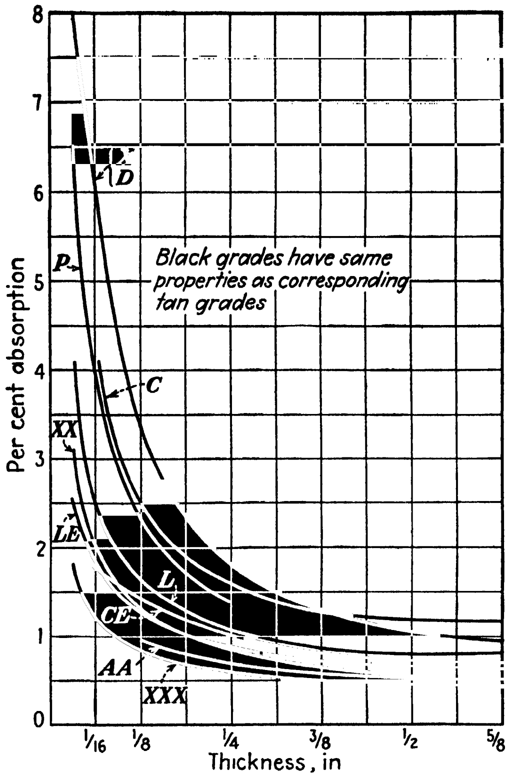


FIG. 276.—Laminated phenolic plate. Maximum water absorption in 24 hr A.S.T.M. method. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

TABLE XXVIII.—PROPERTIES OF LAMINATED PHENOLIC PLATE

Grade	X	P	XX	XXX	C	CE	L	LE	AA	D	S
Punching (maximum thickness of plate):											
Cold	1/32	1/16	......	......	1/16	1/16	1/16	1/16			
Hot	1/16	1/8	1/16	1/16	1/8	1/8	1/8	1/8	......	1/16	
Machining	Fair	Fair	Good	Good	Good	Good	Good	Good	Poor	Fair	Fair
Minimum[g] tensile strength in lb. per sq. in., load applied parallel to the laminations.	9,000	6,000	6,000	5,000	7,500	6,500	7,000	6,500	8,000	8,000	16,000[a] 2,500[b]
Minimum[g] flexural strength, lb. per sq. in.	16,000	11,000	12,000	12,000	16,000	13,000	15,000	15,000	16,000	12,000	20,000[c] 5,000[d]
Minimum compression strength (flatwise) lb. per sq. in.	31,000	19,000	30,000	28,000	35,000	34,000	30,000	33,000	35,000	25,000	17,000
Minimum shearing strength, load applied at right angles to the laminations.	7,000	4,500	5,500	4,000	8,000	8,000	5,500	8,000	10,000	5,000	6,000[e] 2,500[f]
Minimum bond strength, lb. per sq. in. (comparative value for resistance to splitting)	1,450	1,500	1,650	1,600	3,300	3,200	2,050	2,900	1,950	1,450	1,750
Weight, lb. per sq. in.	0.0487	0.0487	0 0487	0.0487	0 0498	0.0498	0 0491	0.0487	0.065	0.0487	0.0462
Specific gravity	1.35	1.35	1 35	1.35	1 38	1.38	1 36	1 35	1.80	1.35	1.28
Minimum dielectric strength, volts per mil on 1/16-in. thickness:											
Short time	500	500	500	500	150	400	150	400	120	500	
Step by step	300	300	300	300	100	240	100	240	75	300	

Grade	X	P	XX	XXX	C	CE	L	LE	AA	D	S
Maximum moisture absorption, per cent after immersion in water for 24 hr at 25°C ± 2°C (test piece 3 × 1 × 1/16)	6	5	2	1 2	4 4	1 8	2 5	1 8	0 95[i]	6 0	
Maximum power factor 10^6 cycles			0 045	0 035		0 065		0 055			
Maximum dielectric constant 10^6 cycles			5 5	5 2		6 0		5 5			
Maximum dielectric loss 10^6 cycles (power factor × dielectric constant)			0 25	0 18		0 4		0 3			
Approximate price relation, per cent, (based on 1/16-in. thick sheet)	100	150	150	190	170	200	200	210	240	85 [h]	200 [h]

Values for dielectric, power factor, and mechanical properties given conform to N E M A ratings They were determined from standard A S T.M. methods of testing (D229)

Values on tensile, flexural, and compressive strength given apply to sheets or plates up to 1 in thickness From 1 to 2 in thickness the minimum values are 10 per cent lower

[a] Load applied parallel to laminations, parallel to the grain

[b] Load applied parallel to laminations, at right angles to the grain

[c] Load applied flatwise, the grain direction spanning the supports

[d] Load applied flatwise, the grain direction at right angles to the span.

[e] Load applied flatwise, across the grain (load tends to break fibers)

[f] Load applied flatwise, parallel to the grain (load tends to split fibers).

[g] Average values (for comparison with other materials) are 30 to 40 per cent higher than minimum standard values.

[h] ½ in thick.

[i] ⅛ in. thick.

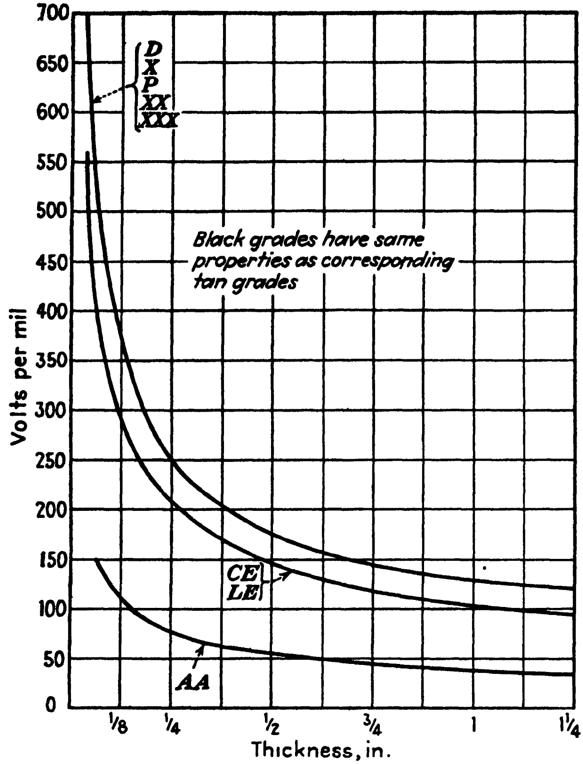


FIG. 277.—Laminated phenolic plate. Minimum dielectric strength, short-time test, perpendicular to laminations. A.S.T.M. method. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

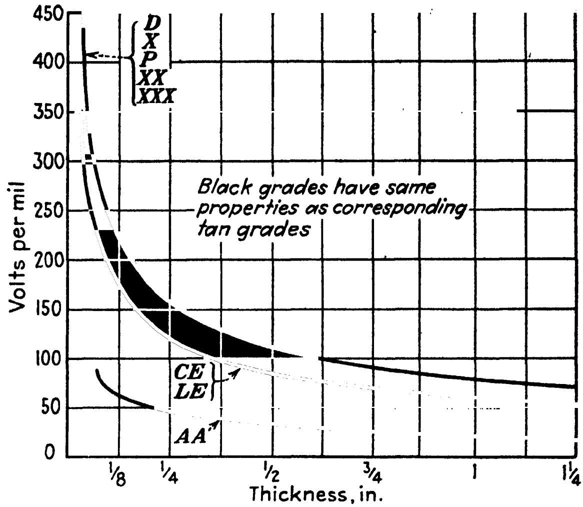


FIG. 278.—Laminated phenolic plate. Maximum dielectric strength, step-by-step test, perpendicular to laminations. A.S.T.M. method. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

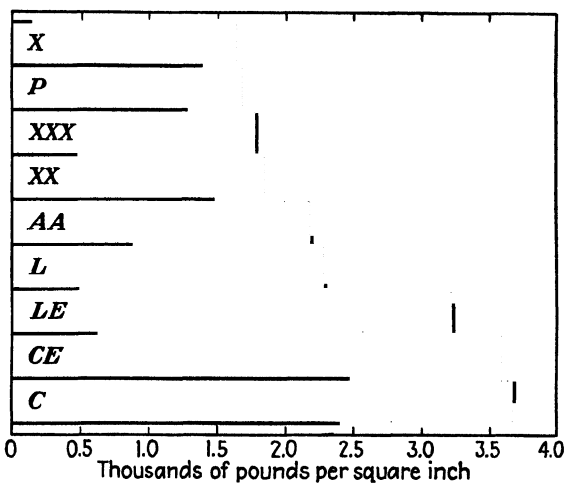


FIG. 279.—Laminated phenolic plate. Bond strength. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

TABLE XXIX.—LAMINATED PHENOLIC RODS

Grade	Color	Standard finish	Base	Average physical strength, lb./sq. in.			Applications
				Tensile	Compression	Flexural	
AA	Brown	Oil	Asbestos fabric	......	......	......	Applications requiring mechanical strength at high temperatures
XX	Tan	Wax	Paper	15,000	20,000	25,000	Good moisture resistance, for electrical purposes
XX	Black	Oil	Paper	15,000	20,000	25,000	Good moisture resistance, for electrical purposes
C	Tan	Wax	Heavy-weave fabric	8,000	21,000	21,000	Mechanical applications where strength is important
LE	Tan	Wax	Fine-weave fabric	10,000	21,000	24,000	For good machinability and good electrical properties
LE	Black	Oil	Fine-weave fabric	10,000	21,000	24,000	For good machinability and good electrical properties

PHYSICAL AND ELECTRICAL PROPERTIES OF LAMINATED PHENOLIC CHANNELS
(Determined by A.S.T.M. standard test methods)

Grade	Color	Base	Average physical strength, lb./sq. in.			Average dielectric strength, volts/mil	
			Tensile	Flatwise compression	Flexural	Short time	Step by step
X	Tan	Paper	12,500	35,000	21,000	700	500
X	Black	Paper	12,500	35,000	21,000	700	500
C	Tan	Heavy-weave fabric	10,000	34,000	19,000		

PHYSICAL AND ELECTRICAL PROPERTIES OF LAMINATED PHENOLIC ANGLES
(Determined by A.S.T.M. standard test methods)

Grade	Color	Base	Average physical strength, lb./sq. in.			Average dielectric strength, volts/mil	
			Tensile	Flatwise compression	Flexural	Short time	Step by step
X	Tan	Paper	12,500	35,000	21,000	700	500
X	Black	Paper	12,500	35,000	21,000	700	500
C	Tan	Heavy-weave fabric	10,000	34,000	19,000		

TABLE XXX.—INSULATING CEMENTS AND COMPOUNDS

Material	Filler	Form	Melting point (ball and ring)	Cold flow °C.	Pour temp., °C.	Specific gravity	Oil resistance	Hardens by	Description and application
Shellac and dextrine	Plaster of Paris	Putty	....	......	.....	2.0	Good	Baking	Low strength, good insulator. Filling spaces back of commutator
Asphalt	Silica	Solid	130	60 to 80	235	1.7	Poor	Cooling	Hard, tough, and nonoilproof
Coal-tar pitch	Silica	Solid	130	60	200 to 235	1.7	Fair	Cooling	Hard, brittle, and oilproof. Sealing bushings in transformers
Bakelite varnish	Silica and mica	Semi-liquid	Infusible	......	...	1.8	Good	Baking	Hard and brittle, filling around turbo end connections
Bakelite varnish	Silica and asbestos	Putty	Infusible	......	...	2.5	Good	Baking	High strength. Filling around turbo end connectors
Varnish	Soapstone	Putty	Infusible	......	...	1.8	Good	Baking	Filling end windings
Shellac	Iron oxide and asbestos	Putty	...	......	...	1.8	Good	Baking	Filling around turbo coils
Bakelite varnish	Silica	Paste	...	......	...	1.4	Good	Baking	Brushed on a.c. generator field coils
Asphalt	Silica	Solid	120	60	190	1.29	Poor	Cooling	Filling around high voltage leads—switchgear
Stearine pitch and montan wax	....	Solid	84	70	175	1.0	Poor	Cooling	Sealing capacitors
Petroleum and asphalt	....	Plastic solid	43 to 47	25	110	0.98	Poor	Cooling	Filling condenser bushings
Varnish	Soapstone and asbestos	Putty	....	......	...	1.8	Fair	Baking	Filling and insulating coils in lifting magnets
Varnish	Soapstone	Semi-liquid	....	......	...	1.7	Good	Baking	Sealing transformer and field coils
Wood pitch and castor oil	....	Solid	63	40	100	1.0	Good	Cooling	Oilproof filling for transformer bushing outlets
Petroleum asphalt	....	Solid	80 to 88	45	150	1.0	Poor	Cooling	Coil impregnation
Petroleum asphalt	....	Solid	110 to 118	60	175	1.02	Poor	Cooling	Coil impregnation

TABLE XXXI.—PROPERTIES OF MYCALEX

Electrical:	
Dielectric strength, ⅛-in. thickness	315 volts/mil
Volume resistivity, 35°C	8.65×10^{11} ohm-cm.
Volume resistivity, 441°C	3.8×10^{10} ohm-cm.
Power factor, 10^6 cycles	0.11 %
Dielectric constant, 10^6 cycles	7.5
Arc resistance	Self-healing surface
Mechanical:	
Specific gravity	3.4
Moisture absorption	Negligible
Tensile strength, 5⁄16-in. rod	12,800 lb./sq. in.
Flexural strength, ½ × ½-in. rod	12,450 lb./sq. in.
Compressive strength	37,800 lb./sq. in.
Thermal:	
Thermal conductivity	0.00104 cal./(cc.)(°C.)(sec.)
Coefficient linear expansion, 0 to 100°C	0.085×10^{-4}
Safe temperature	400°C.
Machining:	
Can be machined, preferably with tungsten carbide tools	

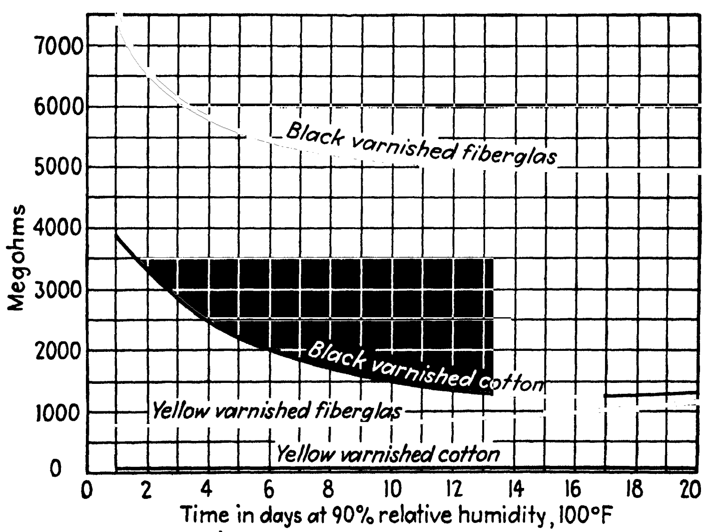


FIG. 280.—Insulation resistance of varnished Fiberglas and cotton cloths. (*Courtesy of Owens-Corning Fiberglas Corp.*)

TABLE XXXII —PROPERTIES OF SOME CERAMIC INSULATING MATERIALS*

Property	Steatite (magnesium silicate) Alsimag #197 good mechanical strength high resistance at high temperature	Steatite (magnesium silicate) Alsimag #211 low loss	Rutile (titanium dioxide) Alsimag #190 high dielectric constant low loss	Grade A lava, natural fired aluminum silicate
Specific gravity	2 5	2 6	3 9	2 3
Per cent water absorption	0 10 to 0 30	0 03 to 0 08	0 00 to 0 02	3 5
Safe limit of temperature °C	1 000	900	1 000	1 000
Tensile strength unglazed	6 500 lb /sq in			1 200 lb /sq in
Compressive strength unglazed	75 000 lb /sq in	65 000 lb /sq in	80 000 lb /sq in	20 000 lb /sq in
Dielectric strength 60 cycles 1/4 in thick	180 volts/mil	200 volts/mil	200 volts/mil	80 volts/mil
Volume resistivity 220 volts 60 cycles				
25°C	Above 10^8 megohm-cm			10^6 megohm-cm
550°C	40 megohm cm			2 megohm-cm
875°C	0 6 megohm cm			0 06 megohm-cm
Dielectric constant				
60 cycles	6 5		85	
1 000 kc	6 0	5 8	85	5 0
Power factor				
60 cycles	0 20%		1 5%†	
1 000 kc	0 12%	0 03%	0 01%†	
Loss factor				
60 cycles	1 30		138	
1 000 kc	0 72	0 17	8 5	

* Taken from data of the American Lava Corporation

† From Westinghouse tests on rutile with 5 per cent clay

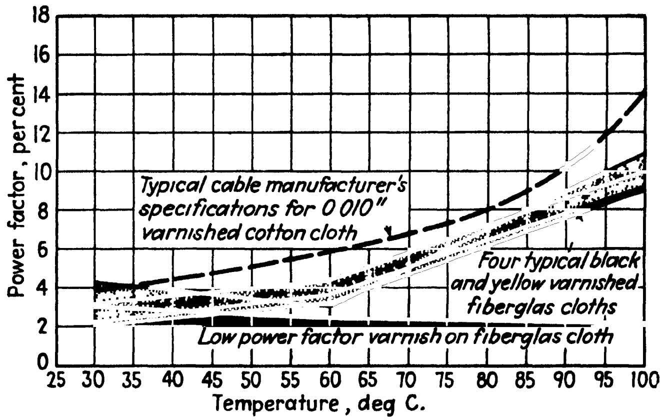


FIG 281 —Power factor of varnished Fiberglas cloths (*Courtesy of Owens-Corning Fiberglas Corp*)

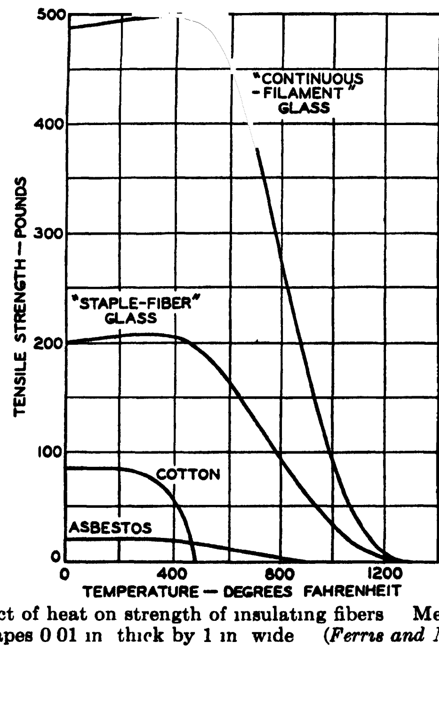


FIG 282 —Effect of heat on strength of insulating fibers Measurements made on tapes 0 01 in thick by 1 in wide (*Ferris and Moses*)

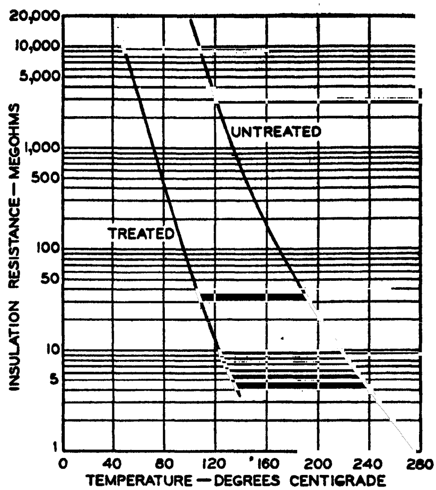


FIG. 283.—Effect of heat on insulation resistance of Fiberglas tape. Measurements made on test coils with 6 layers of 0.01 by 1 in. tape, with contact area of 82 sq. in. (*Ferris and Moses.*)

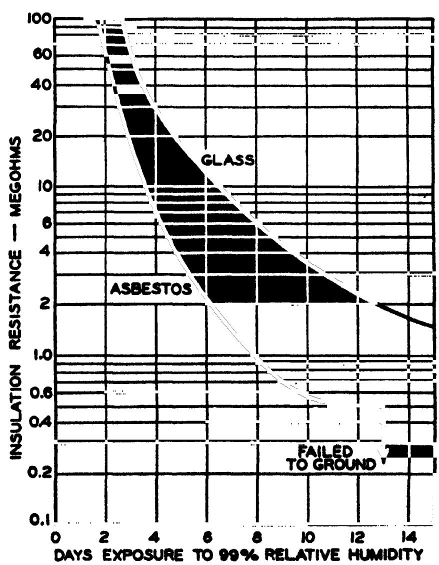


FIG. 284.—Effect of humidity on Fiberglas (and asbestos) insulated coils impregnated with solventless varnish. (*Ferris and Moses.*)

Table XXXIII.—Dimensions of Insulated Magnet Wires*

Size A.W.G.	Size diam.	Diameter over insulation: ASB. max.	S.c.c. wire (max.)	S.c.c.e. wire (max.)	D.c.c. wire (max.)	Enamel wire (max.)	Double-enamel wire (max.)	Single glass heavy wire (max.)	Single glass light wire (max.)	Double glass heavy wire (max.)	Double glass light wire (max.)	S p c e wire (lap) (max.) ½ lap	S p c e wire (rope) (max.) butt	Area of copper: Circ. mils	Area of copper: Sq. in.	Resistance, ohms/1,000 ft.: 25°C. (77°F.)	Resistance, ohms/1,000 ft.: 75°C. (167°F.)	Size diam.
41	0 0028													7 840	0 000006158	1349 0	1609 0	0 0028
40	0 0031					0 0037	0 0040							9 888	0 000007766	1069 0	1276 0	0 0031
39	0 0035					0 0041	0 0044							12 47	0 000009793	848 1	1012 0	0 0035
38	0 0040					0 0047	0 0050							15 72	0 00001235	672 6	802 2	0 0040
37	0 0045					0 0052	0 0055							19 83	0 00001557	533 4	636 2	0 0045
36	0 0050			0 0108		0 0058	0 0061	0 0101	0 0086		0 0121			25 00	0 00001964	423 0	504 5	0 0050
35	0 0056		0 0107	0 0114		0 0064	0 0067	0 0107	0 0092		0 0127			31 52	0 00002476	335 5	400 1	0 0056
34	0 0063		0 0114	0 0122		0 0072	0 0077	0 0114	0 0099		0 0134			39 75	0 00003122	266 0	317 3	0 0063
33	0 0071		0 0122	0 0130		0 0080	0 0085	0 0122	0 0107		0 0142			50 13	0 00003937	211 0	251 6	0 0071
32	0 0080		0 0131	0 0141	0 0171	0 0091	0 0096	0 0131	0 0116	0 0171	0 0151			63 21	0 00004964	167 3	199 5	0 0080
31	0 0089		0 0140	0 0150	0 0180	0 0100	0 0105	0 0140	0 0125	0 0180	0 0160			79 70	0 00006260	132 7	158 2	0 0089
30	0 0100		0 0151	0 0163	0 0191	0 0113	0 0118	0 0151	0 0136	0 0191	0 0171	0 0148		100 5	0 00007894	105 2	125 5	0 0100
29	0 0113		0 0164	0 0176	0 0204	0 0126	0 0131	0 0164	0 0149	0 0204	0 0184	0 0161		126 7	0 00009953	83 44	99 52	0 0113
28	0 0126		0 0177	0 0191	0 0217	0 0141	0 0146	0 0177	0 0162	0 0217	0 0197	0 0176		159 8	0 0001255	66 17	78 93	0 0126
27	0 0142	0 023	0 0193	0 0207	0 0233	0 0157	0 0162	0 0193	0 0178	0 0233	0 0213	0 0192		201 5	0 0001583	52 48	62 59	0 0142
26	0 0159		0 0211	0 0225	0 0251	0 0175	0 0180	0 0211	0 0196	0 0251	0 0231	0 0210		254 1	0 0001996	41 62	49 64	0 0159
25	0 0179	0 027	0 0231	0 0247	0 0271	0 0197	0 0202	0 0231	0 0216	0 0271	0 0251	0 0232		320 4	0 0002517	33 00	39 36	0 0179
24	0 0201	0 029	0 0253	0 0269	0 0293	0 0219	0 0224	0 0253	0 0238	0 0293	0 0273	0 0254		404 0	0 0003173	26 17	31 22	0 0201
23	0 0226		0 0278	0 0294	0 0318	0 0244	0 0249	0 0278	0 0263	0 0318	0 0298	0 0279	0 0267	509 5	0 0004002	20 76	24 76	0 0226
22	0 0254	0 035	0 0307	0 0325	0 0347	0 0275	0 0282	0 0307	0 0292	0 0347	0 0327	0 0310	0 0298	642 4	0 0005046	16 46	19 63	0 0254

Values below conform to those published by the U.S. Bureau of Standards, *Circ.* 31 (Area of copper, Resistance, Size diam. columns).

21	0 0285	0 038	0 0338	0 0356	0 0378	0 0306	0 0313	0 0338	0 0323	0 0378	0 0358	0 0341	0 0329	810 1	0 0006363	13 05	15 57	0 0285
20	0 032	0 041	0 0373	0 0391	0 0413	0 0341	0 0348	0 0373	0 0358	0 0413	0 0393	0 0376	0 0371	1,022	0 0008023	10 35	12 35	0 032
19	0 036	0 045	0 0413	0 0433	0 0453	0 0383	0 0391	0 0413	0 0398	0 0453	0 0433	0 0418	0 0413	1 288	0 001012	8 210	9 792	0 036
18	0 040	0 049	0 0457	0 0477	0 0497	0 0427	0 0435	0 0457	0 0442	0 0497	0 0477	0 0462	0 0457	1,624	0 001276	6 510	7 765	0 040
17	0 045	0 054	0 0508	0 0528	0 0548	0 0478	0 0486	0 0508	0 0488	0 0548	0 0523	0 0513	0 0508	2,048	0 001609	5 163	6 158	0 045
16	0 051	0 060	0 0563	0 0583	0 0603	0 0533	0 0541	0 0563	0 0548	0 0603	0 0583	0 0568	0 0561	2,583	0 002028	4 094	4 884	0 051
15	0 057	0 066	0 0627	0 0651	0 0667	0 0602		0 0627	0 0612	0 0667	0 0647	0 0637	0 0630	3 257	0 002558	3 247	3 873	0 057
14	0 064	0 074	0 0697	0 0772	0 0737	0 0672		0 0697	0 0682	0 0737	0 0717	0 0707	0 0700	4 107	0 003225	2 575	3 071	0 064
13	0 072	0 082	0 0777	0 0802	0 0817	0 0752		0 0777	0 0762	0 0817	0 0797	0 0787	0 0780	5,178	0 004067	2 042	2 436	0 072
12	0 081		0 0866	0 0891	0 0906	0 0841		0 0866	0 0851	0 0906	0 0886	0 0876	0 0869	6,530	0 005129	1 619	1 931	0 081
11	0 091	0 102	0 0967	0 0991	0 101			0 0958		0 1010			0 0969	8 234	0 006467	1 284	1 532	0 091
10	0 102	0 113	0 1079	0 1104	0 112			0 1070		0 1120				10 380	0 008155	1 018	1 215	0 102
9	0 114				0 126					0 1260				13 090	0 01028	0 8077	0 9633	0 114
8	0 129	0 145			0 143					0 1430				16,510	0 01297	0 6405	0 7640	0 129
7	0 144				0 160					0 1600				20,820	0 01635	0 5080	0 6059	0 144
6	0 162				0 178					0 1780				26,250	0 02062	0 4028	0 4805	0 162
5	0 182				0 200					0 2000				33,100	0 02600	0 3195	0 3810	0 182
4	0 204				0 222					0 2220				41,740	0 03278	0 2533	0 3022	0 204
3	0 229				0 247					0 2470				52,640	0 04134	0 2009	0 2396	0 229
2	0 258				0 276					0 2760				66,370	0 05213	0 1593	0 1900	0 258
1	0 289				0 307					0 3070				83,690	0 06573	0 1264	0 1507	0 289
0	0 325				0 343					0 3430				105,500	0 08289	0 1002	0 1195	0 325
00	0 365													133,100	0 1045	0 07947	0 09478	0 365
000	0 410													167,800	0 1318	0 06302	0 07516	0 410
0000	0 460													211,600	0 1662	0 04998	0 05961	0 460

* Westinghouse data

Lamination Insulation.—The objective of low eddy-current losses to be obtained by laminating the cores of transformers, alternating-current machines, and induction regulators is defeated if the surface insulation on the sheets is too low. For some purposes, the natural iron oxide produced by the annealing operation is sufficient insulation. Often, a coating of varnish, enamel, or sodium silicate is applied as additional insulation. The virtue of a sufficient insulating film is shown by a test on a certain small transformer. When laminations with an adequate film were used, the core loss was 35 watts. Sheets thoroughly cleaned of coating and oxide were then assembled, and the same transformer had a core loss of 700 watts. The following tables show some test results under various conditions.

TABLE XXXIV

Punched from bare sheets	Resistivity, ohm-cm.	
	Range	Average
Annealed	0 3 to 7.5	3.84
Burrs ground and annealed	0.33 to 7.9	3.85
Enameled	47 to 480	169
Annealed and enameled	200 to 1,300	493
Burrs ground and enameled	180 to 2,000	587
Burrs ground, annealed and enameled	165 to 2,000	693
Punched from enameled sheets, no treatment	7 to 320	113

TABLE XXXV.—TEST ON PLATES 4 BY 7 IN., DEBURRED AND THEN COATED

Sample	Treatment	Pressure, lb./sq. in.	Resistivity, ohm-cm.
2	2 coats water glass	150	34,300
3	2 coats water glass	150	31,500
7	1 coat varnish	150	27,000
2	....	3,600	3,810
3	....	3,600	4,220
7	....	3,600	27,200

We may conclude from this that varnish resists the crushing of the insulating film by excessive pressures better than water glass.

TABLE XXXVI.—SPECIFIC HEAT AND GRAVITY*
(Specific heat and gravity of insulating materials)

Material	Specific heat		Specific gravity	Volumetric thermal capacity	Thermal conductivity, cal./(sec.)(cc.)(°C.)
Water, 4°C.		1.00	1.00	1.00	
Raw Materials					
Cotton tape, untreated, 0.007 in. thick	80°C.	0.345	0.633	0.218	0.000187
Mica tape, untreated, paper base, 0.006 in. thick	80°C.	0.272	1.363	0.371	0.000630
Asbestos cloth tape, untreated, 0.015 in. thick	80°C.	0.328	1.172	0.385	0.000190
Fish paper, untreated, 0.010 in. thick	......	0.557	1.300	0.724	0.000410
Pressboard, untreated, 0.125 in. thick	80°C.	0.523	0.940	0.492	0.000847
Mica white, untreated, 0.010 in. thick	80°C.	0.210	2.780	0.584	0.0018
Rubber, from insulated wire, untreated	80°C.	0.465	0.980	0.456	0.0043
Paraffin	20°C.	0.694			
Composite Materials					
Varnished cloth, tan 0.008 in. thick	80°C.	0 439	1.162	0.510	Transverse, 0.000516 Longitudinal 0.001027
Varnished cloth, tan 0.017 in. thick	80°C.	0.388	1.104	0.428	
Pressboard impregnated Wemco A oil, 0.125 in. thick	80°C.	0.515	1.210	0.623	
Micarta tubing, bakelite band	80°C.	0 382	1.227	0.469	0.000606
Mica plate, 0.050 in. thick, shellac bond	80°C.	0.223	2.31	0.515	
Mica wrapper, 0.006 in. thick, shellac paper, uncured, 0.003 in. thick	80°C.	0.315	1.22	0.385	
Mica wrapper, 13,200 volts insulated shellac bond, cured	80°C.	0.282	1.305	0.368	Transverse, 0.000553 Longitudinal 0.002700
Mica tape, 13,200 volts insulated shellac band, cured	80°C.	0.250	1.600	0.400	

* Westinghouse data.

TABLE XXXVII.—DIELECTRIC STRENGTH OF COTTON YARN AND TAPE*

Two 1/8-in. square cotton-covered (0.016 in. total thickness) wires 8 in. long, taped together with 1 layer of 0.007 in. cotton tape, and ends bent away from each other for test Puncture voltage between wires recorded (thickness of cotton on two wires)	Breakdown voltage		
	Max.	Min.	Ave.
Double cotton covered and 1 dip in black plastic coil varnish	1,300	1,100	1,190
Double cotton covered and 2 dips in black plastic coil varnish	1,375	1,275	1,350
Double cotton covered and 3 dips in black plastic coil varnish	1,275	1,150	1,195
Double cotton covered and impregnated with asphalt gum	6,500	1,550	3,895
Triple cotton covered and 1 dip in black plastic coil varnish	2,425	1,775	2,045
Triple cotton covered and 2 dips in black plastic coil varnish	2,450	1,925	2,255
Triple cotton covered and 3 dips in black plastic coil varnish	2,525	1,925	2,245
Triple cotton covered and impregnated with asphalt gum	11,500	4,850	8,030

Cotton tape 1 layer half lapped (values are for 1 thickness only)	Breakdown voltage		
	Max.	Min.	Ave.
0.004 cotton tape, no varnish	575	325	450
0.004 cotton tape, 2 dips in black varnish	1,650	400	1,010
0.004 cotton tape, 2 dips in black plastic varnish	850	625	775
0.007 cotton tape, no varnish	950	800	880
0.007 cotton tape, 2 dips in black varnish	1,400	975	1,190
0.007 cotton tape, 4 dips in black varnish and sanded after the second dip	5,600	1,750	3,250
0.007 cotton tape, 6 dips in black varnish and sanded after the third dip	9,500	3,250	5,810
0.007 cotton tape, 2 dips in black plastic varnish	1,025	675	865

* Westinghouse data.

Table XXXVIII.—Dielectric Breakdown of Cloths and Papers*

Untreated Cloths and Tapes

The breakdown of untreated dry fabrics free from conducting materials should be considered the same as equivalent air spacing, *viz.*, 56 volts per mil.

Treated Cloths

When tested in sheet form between 2-in. electrodes, the instantaneous breakdown voltage of tan varnished cloths will average 1,000 volts per mil and the black cloths 1,200 volts per mil minimum.

Friction Tapes

The friction tapes will average 1,000 volts per mil breakdown.

Untreated Papers

Material	Thickness, in.	Breakdown volts/mil
Asbestos paper (nonferrous)	0.007 to 0.010	80
Asbestos paper (regular)	0.015 to 0.063	40
Asbestos millboard	$\frac{1}{8}$ to $\frac{3}{4}$	30
Fish paper	0.004 to 0.015	300
Fish paper	Over 0.015	250
Pressboard	0.007 to 0.010	200
Pressboard	0.015	175
Pressboard	0.034 to 0.078	150
Pressboard	Over 0.078	125
Pressboard	0.056 to 0.125	150
Condenser tissues	0.00035 to 0.00115	300
Japanese tissue	0.001	Air spacing
Glassine paper	0.00075 to 0.0015	300
Rope papers	0.010 to 0.015	60
Rope papers	0.0025 to 0.015	150
Glazed Kraft papers	0.002 to 0.010	150

* Westinghouse data.

TABLE XXXIXA.—INSULATION CLEARANCES
(Agrees with Underwriters Laboratory Code)

Minimum Clearances, in Inches, between Live Parts or Bare Conductors; Indoor Application in Air

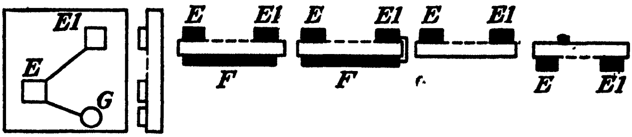
Creeping distances. When mounted on same surface of insulating panels as shown in Fig. 1 only*			Voltage class. For intermediate voltages, it is advisable to use the distances given for the next higher voltage class	Striking distances, when rigidly supported and clear of surface		
Clearance class				Clearance class		
A	B	C		A	B	C
¼	⅜		Up to 50	⅛	¼	
⅜	½	1†	125	¼	⅜	½†
½	⅝	1¼†	250	¼	⅜	¾†
¾	1	2†	600	⅜	½	1†
..	1¼	2⅛	750	..	¾	1¼
..	1¾	2½	1,500	..	1¼	1¾
..	2½	3	2,500	..	2	2½
..	3	3½	3,500	..	2½	3

For voltages above 3,500, all live parts should be supported on insulating pillars.

Clearances in table above do not apply within the proximity of an electric arc. Where arcs are likely to occur, noncombustible barriers should be used for voltages above 250 volts d.c. or 500 volts a.c.

* Where conditions are similar to Figs. 2, 3, or 4 greater spacings are required. For Fig. 5, smaller spacings may be used.

† Conforms to Underwriters Laboratories Standards (National Electrical Code).



Vertical Mounting Fig. 1 | Vertical or Horizontal Mounting Fig. 2 Fig. 3 | Horizontal Mounting Fig. 4 Fig. 5

E and E 1—Parts of opposite polarity.
F—Conducting material.
G—Ground.
............—Creeping distances over surface.

TABLE XXXIX*B*.—CLEARANCE CLASS

Equipment	Between parts of opposite polarity	Between live parts and ground
Switchboards:		
Circuits connected to systems up to 150 kva. capacity	B	A
Circuits connected to systems above 150 kva. capacity	C	B
Panel boards controlling light and power	C	B

PERMANENTLY GROUNDED CIRCUITS. Where one side of a circuit is permanently grounded, the clearance class for parts of opposite polarity should be used

VOLTAGE LIMITS FOR PANEL MATERIALS. Slate up to 750 volts; marble up to 2,500 volts; Micarta and ebony asbestos lumber up to 3,500 volts for panels

TABLE XXXIX*C*.—HIGH-VOLTAGE CONDUCTORS

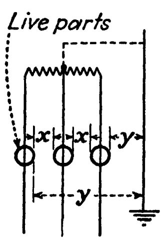
Minimum Clearances, in Inches, between Live Parts or Bare Conductors in Air

For rigid conductors only
When supported clear of surface
For flexible conductors, increase clearances given by twice the maximum sag
Smaller spacings may be used for standard apparatus when all parts are shaped to minimize electrostatic stresses

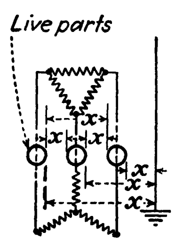
TABLE XXXIXC.—HIGH-VOLTAGE CONDUCTORS.—(*Continued*)

Indoors		Voltage class. For intermediate voltages, it is advisable to use the distances given for the next higher voltage class	Outdoors	
Phase to phase, x	Phase to ground, y		Phase to phase, x	Phase to ground, y
....	....	Up to 3,500	6	6
3½	2½	4,500	6	6
4	3¼	7,500	6	6
7	5½	15,000	12	9
11	8½	25,000	17	13
16	12	37,000	24	18
21	16	50,000	32	23
30	23	73,000	44	32
36	28	88,000	52	38
45	34	110,000	64	47
54	41	132,000	77	56
63	47	154,000	89	65
76	57	187,000	106	78
89	67	220,000	124	90

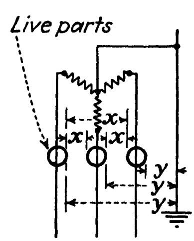
x, y (see Figs. 6 to 8).



Single phase or quarter phase with neutral grounded or ungrounded.
Fig. 6



Three phase, delta or star connected, ungrounded.
Fig. 7



Three phase, star connected, grounded neutral.
Fig. 8

Voltage classes up to 73,000 inc. are maximum allowable

Voltage classes above 73,000 are nominal and a variation of ±5 % may be allowed, without changing the values given on this sheet

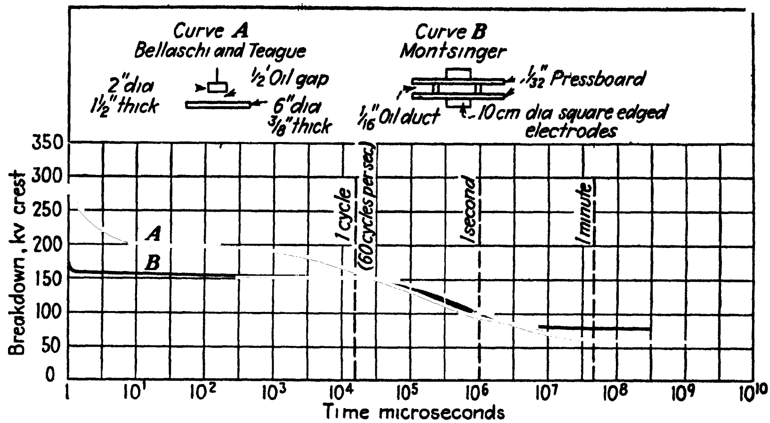


FIG 285 —Impulse breakdown of oil gaps showing regions of constant breakdown

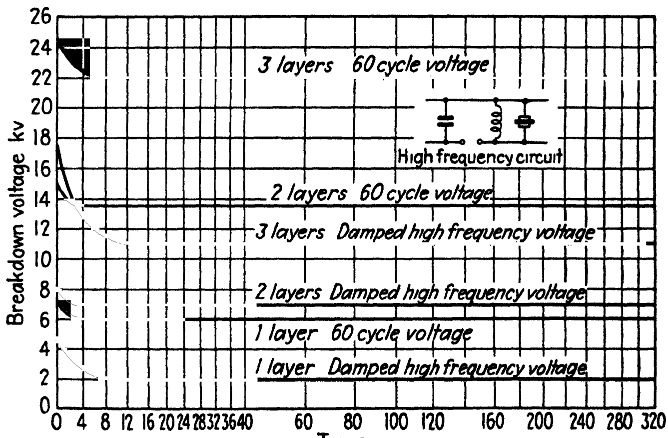


FIG 286 —Time-voltage curves of fish-paper and mica wrappers, 012 in per layer (*Courtesy of Westinghouse Electric & Manufacturing Co*)

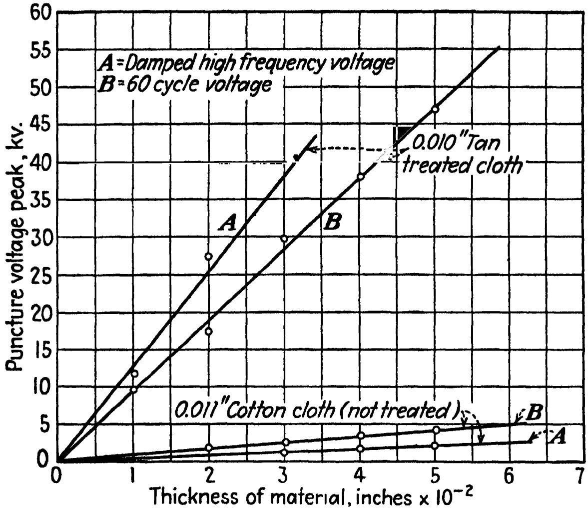


Fig. 287.—Voltage-thickness curves of cloth. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

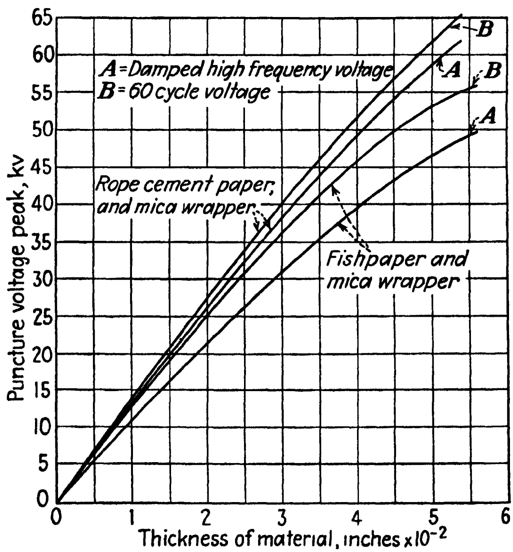


Fig. 288.—Voltage-thickness curves of paper and mica. (*Rylander.*)

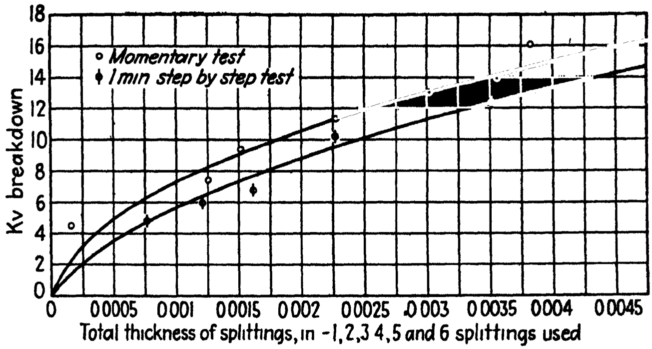


Fig. 289 —Dielectric strength of mica splittings (*Courtesy of Westinghouse Electric & Manufacturing Co*)

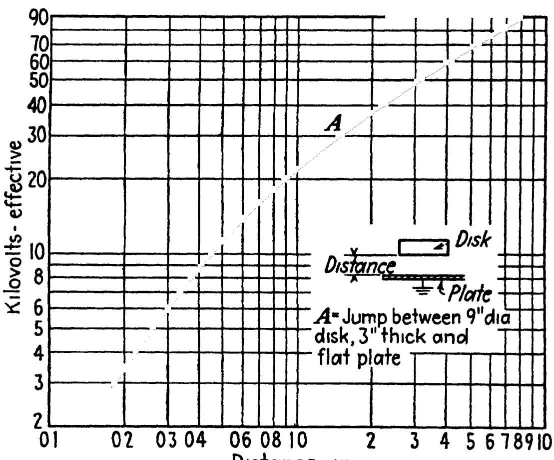


Fig. 290 —Breakdown between sharp edges in air (*Courtesy of Westinghouse Electric & Manufacturing Co*)

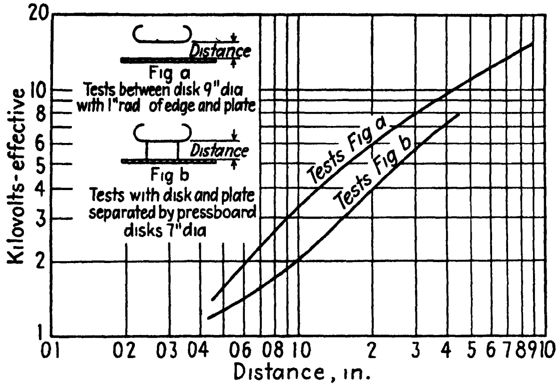


FIG 291.—Breakdown of gaps and surface breakdown with rounded-edged electrode to plate in air (*Courtesy of Westinghouse Electric & Manufacturing Co*)

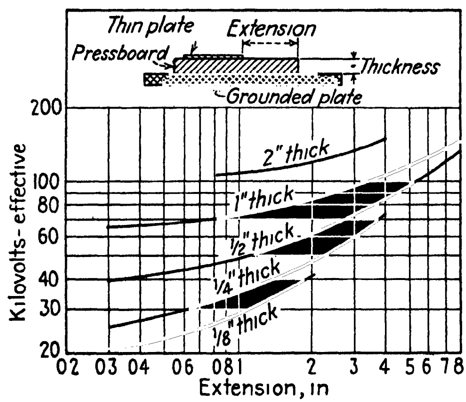


FIG. 292.—Creepage tests over oil-impregnated pressboard, in oil. (*Courtesy of Westinghouse Electric & Manufacturing Co*)

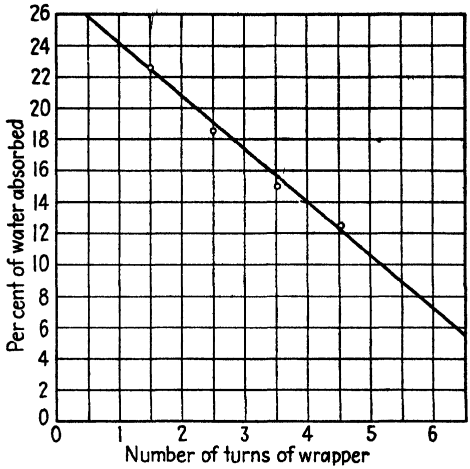


FIG 293 —Moisture absorption of fish-paper and mica wrapper after 24 hr. immersion (*Courtesy of Westinghouse Electric & Manufacturing Co*)

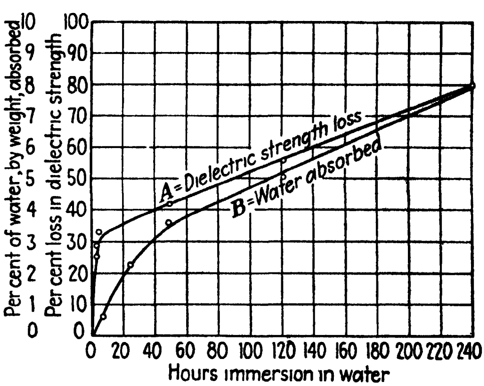


FIG. 294 —Moisture absorption and dielectric strength of varnish-treated cloth, 0 010 in thick (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

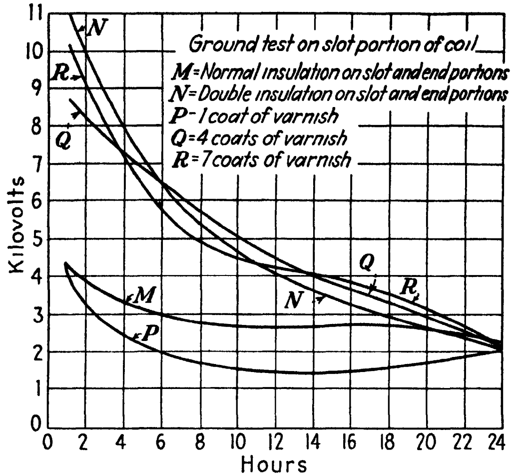


FIG. 295 —Effect of immersion in water on the dielectric strength of armature coil insulation (*Courtesy of Westinghouse Electric & Manufacturing Co*)

APPENDIX B

PERFORMANCE OF INSULATION

GENERAL PRINCIPLES UPON WHICH TEMPERATURE LIMITS ARE BASED IN THE RATING OF ELECTRICAL MACHINERY AND APPARATUS[1]

AN INTRODUCTION TO THE A.I.E.E. STANDARDS

A. General Concepts.—In choosing temperature rise values suitable for particular conditions, the following general concepts may be useful:

1. Insulation does not fail by immediate breakdown upon arrival at some critical temperature, but by gradual mechanical deterioration with time. Therefore, the question of how hot an insulation can be operated can be answered only on the basis of how long it is desired to have it last.

Both time and temperature have the effect of decreasing the mechanical strength of organic material resulting in its becoming less strong and more brittle, and eventually causing it to disintegrate under the influence of vibrations or severe mechanical forces.

2. The electrical strength of insulation can not be directly correlated with its mechanical strength. Generally the dielectric strength increases initially while the mechanical strength decreases owing to the removal of moisture. It then starts to decrease but does not fall below its initial strength until practically all its mechanical strength is gone. Electrical failure will finally result from this physical disintegration.

Thus, how long an insulation will last electrically will depend not only on the class of material used, but also on the effectiveness of the physical support for the insulation, and the severity of the physical forces tending to disrupt it. Even though portions of insulation structures of organic materials have become oxidized or embrittled under the influence of high temperatures, successful operation of the windings may be obtained over further periods of years, if such insulation is not mechanically disturbed.

In view of the important influence of mechanical stresses, thermal expansion and contraction forces impose temperature rise limitations on larger apparatus, even though higher temperature rises have proved to be satisfactory in smaller machines.

3. Insulation life is also dependent to a considerable extent upon the access of oxygen, moisture, dirt or chemicals to the interior of the insula-

[1] Extracted from report of A.I.E.E. Coordinating Committee, No. 4, Jan. 30, 1940.

tion structure. At a given temperature, therefore, well-impregnated windings or totally enclosed machines may have much longer insulation life than windings freely exposed to industrial atmospheres. Particularly favorable results are indicated from the use of chemically inert gases as cooling or protective media.

4. How long an insulation will last in terms of years is also a question of how much of the time it is used and how much load is carried during the actual period of use. These factors of intermittent use and of variable loading are especially important in some of the smaller types of apparatus.

5. It is also important to realize that the physical deterioration of insulation, under the influence of time and temperature, increases very rapidly with temperature. With Class A insulation used in oil-immersed transformers, for example, experience indicates that as a result of chemical changes the insulation life is halved for each approximately 7 to 10°C. increase in temperature, throughout the temperature range of a practical operating interest.

B. Economic Considerations.—The question of what should be considered a desirable life for insulation is largely one of economics. It is tied in with considerations of first cost, reasonable maintenance, obsolescence of electrical and associated mechanical apparatus, the importance of size and weight reductions, etc. In considering such factors, the average, or predominant, conditions should be used as a basis for standards, rather than extreme requirements.

Basis of Rating.—The basis for the assignment of temperature limits for purposes of standardization consists in:

1. Classifying insulation materials in terms of the limiting temperatures which can be reasonably assigned to them.
2. Selecting a reasonable value of limiting ambient temperature, which subtracted from the limiting temperatures gives limiting values of temperature rise.
3. Establishing nominal temperature differences between the readings obtained by the various practical temperature measurement methods, and the limiting insulation temperatures at the selected values of limiting temperature rise.
4. From these, values of limiting observable temperature rise are derived, which are the values used for assigning a rating under specified conditions of test.

It is recognized that temperature rise values permissible in service may differ from those established for rating purposes.

Classification of Insulating Materials.—The temperature limits on which the rating of electrical machines and apparatus is based are largely determined by the character of the insulating materials used.

For the purpose of establishing temperature limits, insulating materials are classified as follows:

Classification of Insulating Materials

Class	Description of Material
O..........	Class O insulation consists of cotton, silk, paper, and similar organic materials when neither impregnated* nor immersed in a liquid dielectric.
A..........	Class A insulation consists of: (1) cotton, silk, paper, and similar organic materials when either impregnated* or immersed in a liquid dielectric; (2) molded and laminated materials with cellulose filler, phenolic resins and other resins of similar properties; (3) films and sheets of cellulose acetate and other cellulose derivatives of similar properties; and (4) varnishes (enamel) as applied to conductors.
B..........	Class B insulation consists of mica, asbestos, fiber glass, and similar inorganic materials in built-up form with organic binding substances. A small proportion of Class A materials may be used for structural purposes only.†
C..........	Class C insulation consists entirely of mica, porcelain, glass, quartz, and similar inorganic materials.

* An insulation is considered to be "impregnated" when a suitable substance replaces the air between its fibers, even if this substance does not completely fill the spaces between the insulated conductors. The impregnating substances in order to be considered suitable, must have good insulating properties; must entirely cover the fibers and render them adherent to each other and to the conductor; must not produce interstices within itself as a consequence of evaporation of the solvent or through any other cause; must not flow during the operation of the machine at full working load or at the temperature limit specified; and must not unduly deteriorate under prolonged action of heat.

† The electrical and mechanical properties of the insulated winding must not be impaired by application of the temperature permitted for Class B material. (The word "impair" is here used in the sense of causing any change which could disqualify the insulating material for continuous service.) The temperature endurance of different Class B insulation assemblies varies over a considerable range, in accordance with the percentage of Class A materials employed, and the degree of dependence placed on the organic binder for maintaining the structural integrity of the insulation.

Use of Methods of Temperature Determination.

1. The thermometer method is preferred for uninsulated windings, exposed metal parts, gases, and liquids; or surface measurements generally; and wherever other methods are not applicable or practical as, for instance, in some cases of windings with very low resistance. Thermocouples are preferred for measuring rapidly changing surface temperatures, as in the case of resistors.

2. The resistance method is preferred for insulated windings, except for very low resistance windings, or where the embedded-detector method is specified.

3. The embedded-detector method is preferred for interior measurements at designated locations as specified in the Standards for certain kinds of apparatus, such as large rotating machines.

Limiting Insulation Temperatures ("Hottest-spot" Temperatures). From the results of experience with apparatus in service, and of laboratory tests on various insulating materials, limiting insulation temperatures (called "hottest-spot" temperatures) have been assigned *for purpose of standardization* The "hottest-spot" temperature is, therefore, the primary point of reference, or the "bench-mark" temperature It is not employed in commercial transactions because it is not directly measurable in the ordinary course of testing or operation of electrical machines.

The values of "hottest-spot" temperatures established for this purpose are as follows

For Class O material	90°C
For Class A material	105°C
For Class B material	130°C
For Class C material	No limit selected

Limiting Values of Insulation Temperature Rise—The limiting values of "hottest-spot" temperature rise of the insulation are obtained by subtracting the 40°C value of limiting ambient temperature from the limiting "hottest-spot" temperature

The values of "hottest-spot" temperature rise so obtained are·

For Class O material	50°C
For Class A material	65°C
For Class B material	90°C
For Class C material	No limit selected

LIMITING OBSERVABLE TEMPERATURE RISE FOR INSULATED WINDINGS OF CONTINUOUS RATED APPARATUS

Method	Class O material, °C	Class A material, °C	Class B material, °C
1 *Air or gas-immersed apparatus*			
Thermometer method	35	50	70
Resistance or embedded-detector method	45	60	80
2 *Mineral oil-immersed apparatus*			
Resistance method		55*	

* This lower value is selected in recognition of the life temperature characteristics of mineral oil Consideration has also been given to the fact that this value is chiefly applicable to transformers which are usually installed outdoors or in other locations where the average ambient temperatures are materially lower than the 40°C value selected as the limiting ambient temperature

TABLE XL —TENSILE TESTS OF INSULATING MATERIAL. EFFECT OF HEAT
(Each figure represents the average of five tests)*

Material	Size in	Heated 200°C for time indicated — Tensile strength lb 5-in length between jaws: As received	5 min	15 min	30 min	2 hr	5½ hr	24 hr
Cotton tape untreated	0 007 × ¾	53	51	47	46	39	10	5 6
Cotton tape treated black plastic varnish once	0 007 × ¾	58	59	56	55	55	19	10 4
Cotton tape treated three times black plastic varnish	0 007 × ¾	60	57	61	60	56	28	18 2
Cotton tape varnished three times clear varnish	0 007 × ¾	76	63	66	66	63	24	3 9
Cotton tape saturated with shellac	0 007 × ¾	83	67	62	50	53	20	2 64
Cotton tape treated with oil	0 007 × ¾	59	58	53	48	37	12	4 42
Asbestos tape untreated	0 015 × ¾	32	37	35	35	31	26	2 6
Rope cement paper untreated	0 005 × ¾	46	42	34	33	32	10	3 0
Rope cement paper treated oil	0 005 × ¾	38	41	33	36	26	10	4 1
Yellow treated cloth	0 010 × ¾	37	34	31	15	40	†	†
Black treated cloth	0 010 × ¾	48	39	44	47	44	20	3 5
Fish paper and mica	0 012 × ¾	46	51	53	51	49	43	2 9
Combination slot cell material (varnished cloth and fish paper)	0 023 × ¾	203	210	142	149	167	73	0 34
Cotton yarn	80 to 20	4 56	5 06	4 32	3 54	2 18	0 85	‡
Japanese tissue	0 001 × ⅛	1 46	1 44	1 22	0 84	0 71	‡	‡
Manila rope paper	0 001 × ⅛	1 62	1 26	1 04	0 78	0 80	0 40	‡
Manila rope paper	0 0015 × 3/16	4 22	3 36	3 60	2 70	2 02	1 18	‡
Wood-pulp paper	0 0015 × 3/16	2 40	2 06	2 16	1 62	1 72	0 96	‡
Japanese tissue treated black plastic varnish	0 001 × 3/16	2 38	2 40	2 44	1 56	1 52	‡	‡
Japanese paper	0 002 × ¼	9 84	8 58	8 80	6 44	4 50	2 24	1 54
Viscose sheet	0 001 × 3/16	1 52	1 66	1 52	1 24	1 52	1 24	1 04
Acetate sheet	0 001 × 3/16	1 12	§	§	§	§	§	¶
Wood-pulp condenser paper	0 001 × 3/16	2 56	2 58	2 38	2 16	2 32	1 66	‡

* Westinghouse data
† Stuck together and too brittle to test
‡ Too brittle and weak to test
§ Curled shriveled and brittle
¶ Completely gone

LOCATION OF INSULATION FAILURES

Post-mortem operations and coroner's findings do not help the unfortunate victim of an accident but something may be learned to prevent future deaths. The coroner for electrical apparatus may be the insurance inspector or the service repairman and their experiences may point the way to better designs. It is a signifi-

cant challenge to find so often that electrical failures are caused by or at least involve the insulation. An enlightening article by K. A. Reed,[1] Chief Engineer, Electrical Division of the Hartford Steam Boiler Inspection and Insurance Company, gives the following picture.

Analysis of 3,439 failures of electrical apparatus shows that insulation failed in 2,917, or 84.8 per cent, of these cases. The following table shows the point of failure for those cases where the cause was definitely determined.

TABLE XLI

Loosening of band wires, wedges, etc	140
Accumulation of foreign matter on windings	142
Carelessness or ignorance of operator	57
Overheating, sustained overload and other causes	133
Excessive moisture in air	139
Flooding and inundation	80
Lightning or line surges	506
Single phasing from all causes	150
Insulation breakdown between turns	202
Insulation breakdown between coils and ground	232
Insulation breakdown between commutator bars or slip rings	95
Insulation breakdown between ground and bars or rings	56
Short circuits in control apparatus, switchboards, etc	100
Total number of definitely classified failures	2,032
Miscellaneous electric failures (not included above)	233
Undetermined causes	652
Grand total electric insulation failures	2 917

Classifying the failures by the most prominent initial point of failure gave the following:

TABLE XLII

Rotor or armature winding	555
Stator winding ..	1,128
Field coils	82
Brush-holder rigging	19
Commutator or collector ring	346
Band wires or wedges	22
Brake coils	46
High-tension winding (transformers)	72
Low-tension winding (transformers)	28
Busses, bushings, instrument transformers, stationary coils	137
Low-voltage releases, relay, overload coil, etc	174

[1] *Elec. Jour.*, vol 32, p 69, 1934.

INSULATION RESISTANCE

Since the resistance of insulation decreases exponentially with increases in temperature, insulation-resistance measurements must be corrected to standard temperatures. In determining whether the insulation resistance of rotating machines indicates good condition or an unsafe margin, the temperature must be taken into account. Several expressions and rules of thumb have evolved to express the change with temperature. A common rule is that the resistance doubles for every 10° decrease in temperature for class A and every 8° for class B insulation. Or, more exactly, the relation may be given by the expression[1]

$$R_2 = R_1 \times (0.44)^n \text{ for class A insulation.}$$
$$R_2 = R_1 \times (0.63)^n \text{ for class B insulation.}$$

where R_1 = resistance at temperature 1.
R_2 = resistance at higher temperature 2.
n = temperature difference (2 − 1) divided by 10.

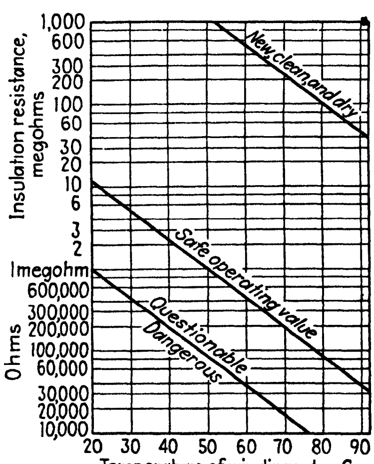


FIG. 296.—Resistance of class A insulation in motors. (*Moses.*)

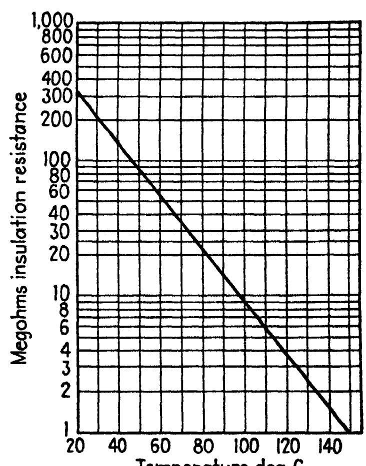


FIG. 297.—Resistance of class B insulation in motors. (*Moses.*)

Figures 296 and 297 indicate the resistance that may be expected in motor insulation, the lowest curve being the danger line.

[1] MOSES, G. L., *Factory Management and Maintenance*, vol. 96, p. 78, July, 1938.

LIFE OF COIL INSULATION AT ELEVATED TEMPERATURES

Short-time accelerated tests on insulation samples are not usually reliable substitutes for long-time tests. Deterioration of most organic insulation involves both mechanical and electrical failures, the latter probably dependent on the former, since, after flexibility is lost, vibration or flexing opens the path for electrical breakdown. Painstaking work has been done to find the behavior of insulation in a form as nearly as possible like shapes

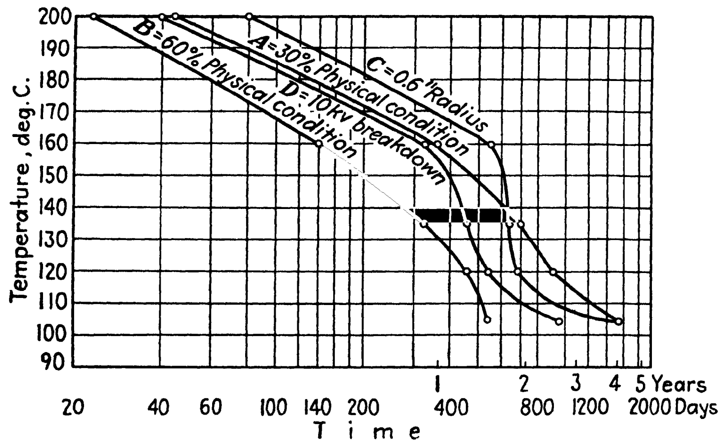


FIG. 298.—Aging curves of class A insulation. *A*, aged until 30 per cent of original physical condition was reached; *B*, aged until 60 per cent of original physical condition was reached; *C*, aged until sample would crack when bent to 0.6-in. radius; *D*, aged until sample would break down at 10 kv. after immersion in water. (*Smith and Scott.*)

occurring in machines, under long exposure to excessive temperatures. A judicious interpretation of the results will do much toward predicting the life of insulation under unavoidable abnormal conditions and keeping the controllable factors of normal service at the most efficient yet safe level of output.

The work of Smith and Scott,[1] extending over a period of 5 years, explored the behavior of class A insulation at various excessive temperatures. The samples were made by wrapping insulation to a thickness of 0.01 in. on a 1½-in. diameter brass tube. Asbestos was applied over the insulation and on the outside a protective layer of varnished cloth 0.08 in. thick. Failure was indicated by observation of physical condition (soft

[1] A.I.E.E., vol. 58, p. 435, 1939.

and flexible = 100; hard and inflexible but not very brittle = 50; completely cracked, charred, and crumbly = 0); by cracking on

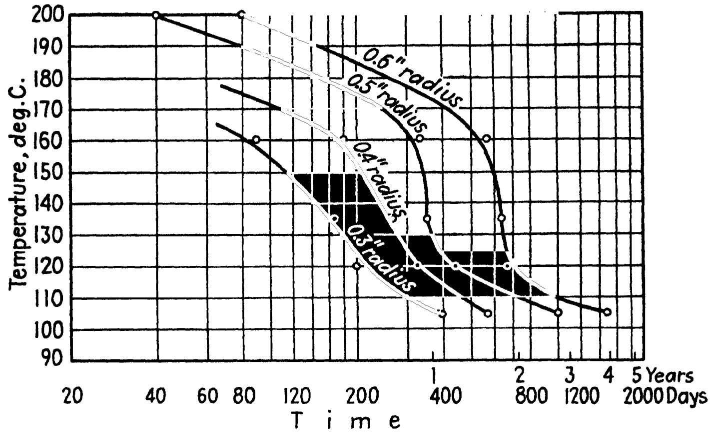


FIG. 299.—Class A insulation. Time to age sufficiently to produce cracking when bent to various radii of curvature. (*Smith and Scott.*)

bending over a mandrel; and by electrical breakdown following immersion in water for 48 hr. Figures 298, 299, and 300 sum-

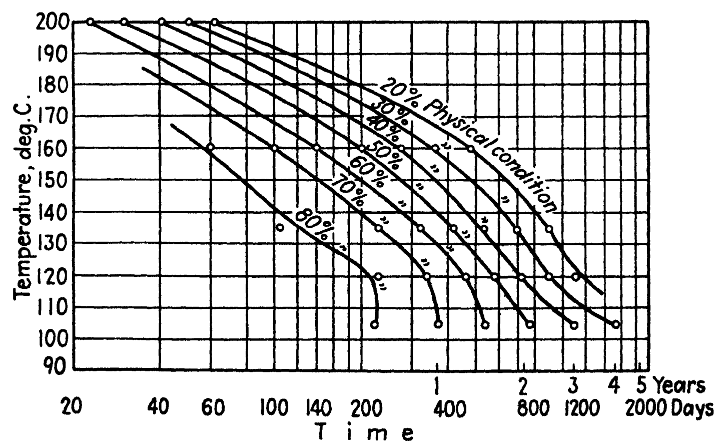


FIG. 300.—Class A insulation. Time to age to various percentages of original physical condition (visual observation). (*Smith and Scott.*)

marize the results. It appears that class A insulation will not withstand temperatures above 105°C. for more than a year without serious damage.

The life of insulation can be expressed by a relation similar to the temperature-resistance formula.

$$L = L^1K^n$$

where L = life at T deg. C.
L^1 = life at T^1 deg. C.
K = life constant.

$$n = \frac{T - T^1}{10}.$$

For class A insulation, K is 0.44. From preliminary data, K for class B may be approximately 0.52. Stated in another way,

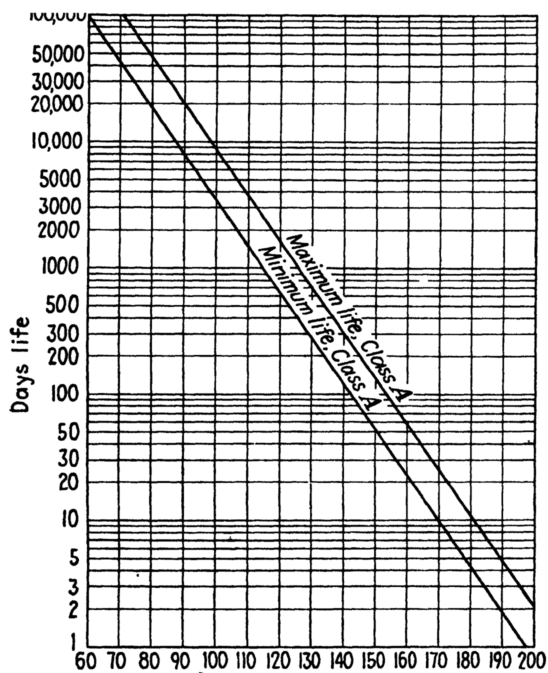


FIG. 301.—Effect of temperature on life of insulation. (*Moses.*)

life of class A insulation is halved for each increase in 8°C. temperature; for class B, the interval is approximately 10½°C. The curve in Fig. 301 is based on considerable practical experience, showing safe estimates of the total life of the class A insulation at various temperatures.

STORAGE OF INSULATION

Insulating Materials.—Deterioration of insulating materials in storage is caused by oxidation and by loss of solvent, or of

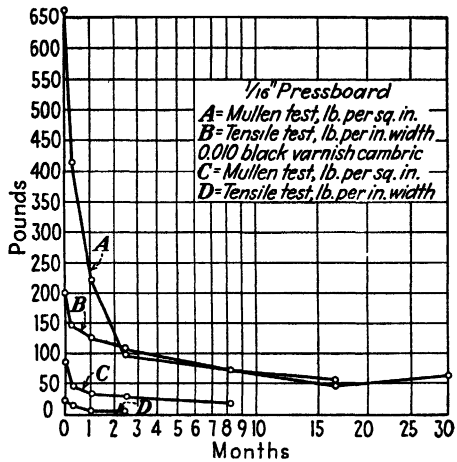


FIG. 302.—Life tests on insulation in oil at 105°C. *A* and *B*, 1/16-in. pressboard; *C* and *D*, 0.010-in. black varnished cloth. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

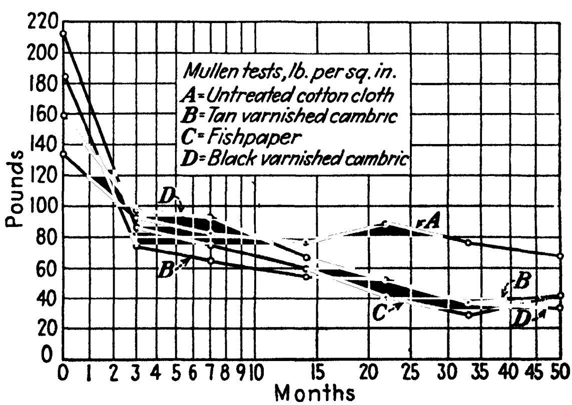


FIG. 303.—Life tests on insulation in air at 95°C. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

moisture. Hence the storage conditions for each class of materials should be designed to minimize the effects of the action that causes trouble in the particular type of material being considered. Time is a factor, and so the precautions to be taken are influenced by the length of time the materials are to be stored.

A storage room should be provided where the air is maintained at an even temperature with a relative humidity of 40 to 50 per cent. The room should be clean and free from dust.

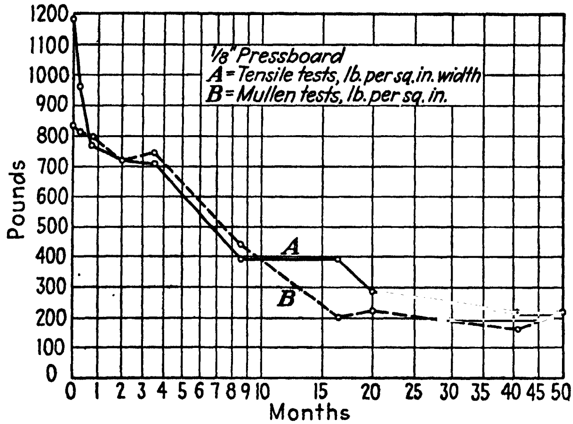


FIG. 304.—Life tests on pressboard in air at 95°C. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

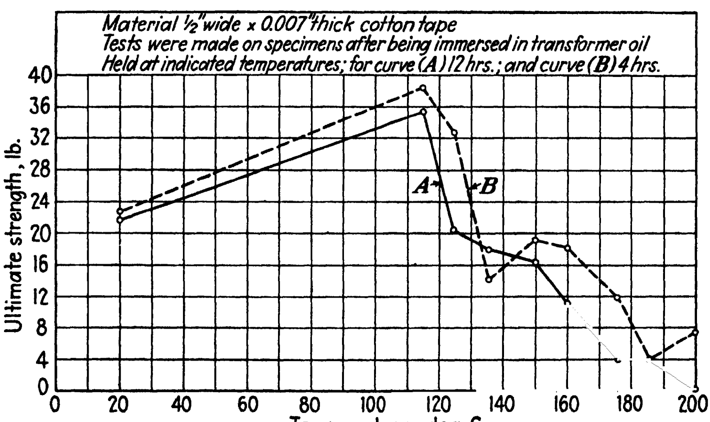


FIG. 305.—Effect of heat on mechanical strength of cotton. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Insulated coils and apparatus, the insulation of which might be injured by bending, should not be handled frequently. Untreated cloths and papers may be stored with sufficient wrapping to keep them clean and dry.

Varnished cloth and papers should be wrapped to prevent too free access of air. Careful wrapping with moistureproof paper and a dip in melted paraffin have been found adequate, or storage in tightly closed tin containers is effective.

Hard fiber and fish papers should not be stored too close to heating equipment or ovens where they may be dried out too thoroughly, for such conditions will make them too brittle to work. These materials should be dried out only after they are in position on the apparatus.

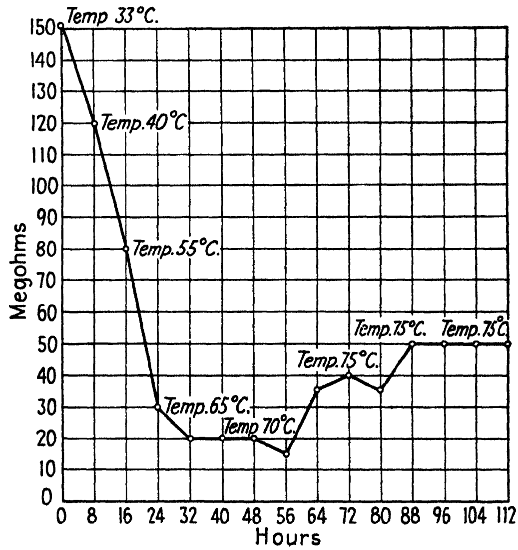


FIG. 306.—Insulation-resistance curve of a 25,000-kva. turbogenerator during progress of drying. (*Courtesy of Westinghouse Electric & Manufacturing Co.*)

Flexible mica tape and wrapper material contain a volatile thinner and must be tightly sealed in tin containers to preserve them.

Coils.—The same general conditions that are suitable for insulating materials are favorable for storing coils. Coils that are small enough to make such procedure practical should be packed and stored in sealed cartons. The larger coils should be housed in wooden boxes or crates, individually or by two or three, depending on the size of the coils and the condition of the shipment. The large coils should have the slot portions blocked and clamped to gauge size to prevent swelling of the wrappers.

They should first be wrapped (on the straight parts) with paraffined paper and the ends taped with varnished cambric tape which, of course, is to be removed in preparing the coil for use. Small coils that are not blocked and clamped, should be examined every few years, if kept in storage for long periods; if at any time the varnish coating is found deteriorating or cracking, they should be given an additional coat of varnish recommended by the supplier, preferably a plastic varnish.

Life of Coil Varnish at Various Temperatures.—The "life" as determined by the standard A.S.T.M. test, which is a measure of loss of flexibility, decreases very rapidly with increase in temperature. For a typical varnish the following table of equivalent lengths of life at various temperatures is representative.

Temperature, °C.	Life, Hr.
105	600
125	150
150	30
200	1.5

APPENDIX C

PLASTICS DIRECTORY*

Common Trade Names in the United States

Name	Type	Manufacturer
Acelose	Cellulose acetate	American Cellulose Corp.
Acrolite	Phenol-glycerol	Continental-Diamond Fiber Co.
Acryloid	Acrylic	Resinous Products & Chemical Co.
Albertol	Phenol-formaldehyde	Rohm and Haas Co.
Ambersol	Phenol-formaldehyde	Resinous Products & Chemical Co.
Amerith	Pyroxylin	Celluloid Corp.
Ameroid	Casein	American Plastics Corp.
Arcolite	Phenol-formaldehyde	Consolidated Molded Products Corp.
Aroclor	Chlorinated diphenyl	Swann Chemical Co.
Beetle	Urea formaldehyde	American Cyanamid Co.
Campbellite	Phenol formaldehyde	Campbell Fiber Co.
Catalin	Phenol formaldehyde	American Catalin Corp.
Celeron	Phenol formaldehyde	Continental-Diamond Fiber Co.
Celluloid	Pyroxylin	Celluloid Corp.
Cetec	Cold-molded	General Electric Co.
Coltrock	Cold-molded	Colt Patent Fire Arms Mfg. Co.
Coltstone	Phenol formaldehyde	Colt Patent Fire Arms Mfg. Co.
Condensite	Phenol formaldehyde	Bakelite Corp.
Cumar	Coumarone	Barrett Co.
Dilecto	Phenol-formaldehyde	Continental-Diamond Fiber Co.
Dilecto U F	Urea formaldehyde	Continental-Diamond Fiber Co.
Dumold	Pyroxylin	E. I. du Pont de Nemours Co.

* Condensed from material in "Modern Plastics Catalogue-Directory," 1939.

COMMON TRADE NAMES IN THE UNITED STATES.—(*Continued*)

Name	Type	Manufacturer
Duranoid	Phenol formaldehyde	Specialty Insulation Mfg. Co.
Durez	Phenol formaldehyde	General Plastics Co.
Durite	Phenol furfural	Stokes & Smith Co.
Durium	Resorcinol formaldehyde	Durium Products Corp.
Ebrok	Bituminous plastic	Richardson Co.
Electrose	Hot-molded shellac	Insulation Mfg. Co.
Enameloid	Pyroxylin	Gemloid Corp.
Erinoid	Casein	American Plastics Corp.
Esterol	Glycerol	Paramet Chemical Co.
Ethocel	Ethyl cellulose	Dow Chemical Co.
Fabroil	Phenol formaldehyde	General Electric Co.
Fiberlac	Pyroxylin	Fiberloid Corp.
Fiberlon	Phenol formaldehyde	Fiberloid Corp.
Fibestos	Cellulose acetate	Fiberloid Corp.
Formica	Phenol formaldehyde and urea formaldehyde	Formica Insulation Co.
Gemloid	Pyroxylin	Gemloid Corp.
Glyptal	Glycerol	General Electric Co.
Hemcoware	Urea formaldehyde	Bryant Electric Co.
Herkolite	Phenol formaldehyde	General Electric Co.
Indur	Phenol formaldehyde	Reilly Tar and Chemical Corp.
Insulate	Hot-molded	Insulation Mfg. Co.
Insurok	Phenol formaldehyde	Richardson Co.
Karolith	Casein	American Plastics Corp.
Kenoid	Phenol formaldehyde	National Vulcanized Fiber Co.
Kyloid	Casein	George Morrel
Lacanite	Shellac	Consolidated Molded Products Corp.
Lamicoid	Phenol formaldehyde	Mica Insulator Co.
Lindol	Pyroxylin	Celluloid Corp.
Lucite	Methacrylate	E. I. du Pont de Nemours Co.
Lumarith	Cellulose acetate	Celluloid Corp.
Makalot	Phenol formaldehyde	Makalot Corp.
Marblette	Phenol formaldehyde	Marblette Corp.
Masuron	Cellulose acetate	J. W. Masury & Sons
Micabond	Mica and shellac	Continental-Diamond Fiber Co.
Micarta	Phenol formaldehyde and urea formaldehyde	Westinghouse Electric & Mfg. Co.

COMMON TRADE NAMES IN THE UNITED STATES.—(*Continued*)

Name	Type	Manufacturer
Moldarta.	Phenol formaldehyde and urea formaldehyde	Westinghouse Electric & Mfg. Co.
Monolite..	Hot-molded	General Electric Co.
Monsanto.	Phenol formaldehyde	Monsanto Chemical Co.
Nacara....	Pyroxylin	Fiberloid Corp.
Neoprene..	Isoprene derivative (synthetic rubber)	E. I. du Pont de Nemours Co.
Nivolak........	Phenol formaldehyde	Bakelite Corp.
Nixonite.......	Cellulose acetate	Nixon Nitration Works
Nixonoid.......	Pyroxylin	Nixon Nitration Works
Panplastic.....	Phenol formaldehyde	American Plastics Corp.
Paracoumarone.	Coumarone and/or indene	Barrett Co.
Paranol........	Phenol formaldehyde	Paramet Chemical Co.
Phenolite......	Phenol formaldehyde and urea formaldehyde	National Vulcanized Fiber Co.
Plaskon...	Urea formaldehyde	Plaskon Corp.
Plastaccle.	Cellulose acetate	E. I. du Pont de Nemours Co.
Plexiglas..	Acrylic	Rohm and Haas
Plioform..	Rubber resin	Goodyear Tire & Rubber Co.
Protecto...	Pyroxylin	Celluloid Corp.
Protectoid.	Cellulose acetate	Celluloid Corp.
Prystal....	Phenol formaldehyde	American Catalin Corp.
Pyroplax..	Cold-molded	Cutler-Hammer Co.
Redmanol.	Phenol formaldehyde	Bakelite Corp.
Resan.....	Phenol formaldehyde	Bakelite Corp.
Resibond..	Phenol formaldehyde	Bakelite Corp.
Resinox....	Phenol formaldehyde	Resinox Corp.
Resisto....	Pyroxylin	Celluloid Corp.
Resoglaz...	Polystyrene	Advance Solvents & Chemicals Co.
Rezyl.........	Glycerol	American Cyanamid Co.
Richelain.....	Urea formaldehyde	Richardson Co.
Richware.....	Phenol formaldehyde	Makalot Corp.
Rubtex.......	Hard rubber	Richardson Co.
Spauldite.....	Phenol formaldehyde	Spaulding Fiber Co.
Stoco.........	Bitumen plastic	Jos. Stokes Rubber Co.
Supermicanite.	Mica and glycerol	Superlithe Corp.
Synthane.....	Phenol formaldehyde	Synthane Corp.
Tenite........	Cellulose acetate	Tennessee Eastman Corp.
Textolite......	Phenol formaldehyde	General Electric Co.
Thermoplax...	Cold-molded	Cutler Hammer Co.

COMMON TRADE NAMES IN THE UNITED STATES.—(*Continued*)

Name	Type	Manufacturer
Thiokol.	Olefin polysulphide (synthetic rubber)	Thiokol Corp.
Tornesit..	Chlorinated rubber	Hercules Powder Co.
Tortaloid.	Cellulose acetate	Fiberloid Corp.
Unyte....	Urea formaldehyde	Plaskon Corp.
Uralite...	Urea formaldehyde	Consolidated Molded Products Corp.
Victron...	Polystyrene	U. S. Rubber Products, Inc.
Vinylite..	Vinyl	Carbide & Carbon Chemical Co.
Viscoloid.	Pyroxylin	E. I. du Pont de Nemours Co.
Vulcoid...	Phenol formaldehyde with vulcanized fiber	Continental-Diamond Fiber Co.
Waterlite.	Polystyrene	Watertown Mfg. Co.

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